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**A METHOD OF COMPUTING SHIP CONTRAST TEMPERATURES
INCLUDING RESULTS BASED ON WEATHER SHIP J
ENVIRONMENT DATA**

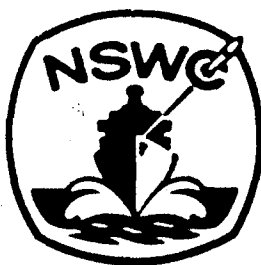
BY DONALD M. WILSON

RESEARCH AND TECHNOLOGY DEPARTMENT

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A computer program based on the Single Element Method is described and ship contrast temperature calculations are given. This program models a specific ship, the U.S. Navy Patrol Frigate. However, the choice of ship model is shown to be not critical provided that stack cooling is assumed. The program was run with weather data gathered by Weather Ship J over an 8 year period (1964-71). Results are given as the probability of observing a given contrast temperature or lower values over a 4 month season. The effect of target ship heading and season on contrast temperatures is analyzed and discussed. A general recommendation of expected contrast temperatures is made for the weather data of this study.

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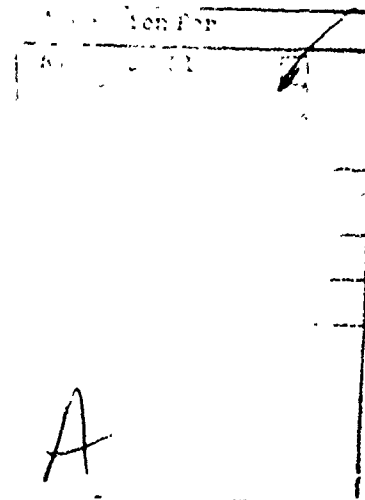
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SUMMARY

This report represents work done to support electro-optical programs at the Dahlgren Laboratory of the Naval Surface Weapons Center. It presents analytical methods which were developed to predict ship signatures which include weather effects. These are given as ship contrast temperatures that are used in computer programs to predict the performance of present optical systems used for infrared detection and tracking (8-12 μ waveband). This report also presents contrast temperature predictions for weather data taken by ship J during the years 1964-71. Future efforts will center on signature predictions for other locations and on the expansion of the analytical models to include other ship targets and background conditions. This work was sponsored by Code N54 of the Naval Surface Weapons Center.

Paul R. Wessel

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By direction



CONTENTS

	<u>Page</u>
I. INTRODUCTION	5
II. BACKGROUND	7
III. HEAT TRANSFER RATES USED IN SINGLE ELEMENT METHOD	12
IV. SINGLE ELEMENT METHOD FOR CALCULATION OF SHIP TEMPERATURE	16
V. CONTRAST TEMPERATURE CALCULATION	22
VI. RESULTS	26
VII. CONCLUSION	54
VIII. SYMBOLS	57
APPENDIX A	A-1
APPENDIX B	B-1

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Angles Determining Effective Sea Surface Emissivity	9
2	Composition of Sea Surface or Background Radiance	10
3	Determination of Direct Solar Radiance on a Vertical Surface	13
4	Comparison of Sea Surface Radiance and Radiance Calculated from Background Temperatures for the 8-12 μ m Waveband	24
5	Blackbody Radiance in 8-12 μ m Waveband	24
6	Incident Solar Energy on a Vertical Element for Various Ship Headings at Longitude 52°N	28
7	Probability of Observing Effective Ship Temperature	30
8	Probability of Observing Reflected Sky Temperature	31
9	Representative Probability of Observing Background Temperature . . .	32
10	Probability of Observing Daytime Contrast Temperatures	33
11	Probability of Observing Maximum Contrast Temperatures	34
12	Probability of Observing Nighttime Contrast Temperatures	35
13	Probability of Observing Total Contrast Temperatures	38
14	Representative Probabilities of Observing Daytime Contrast Temperatures for Various Ship Headings	39
15	Probability of Observing Ship Contrast Temperatures with Sea Level Background	40
16	Probability of Observing Temperature Correction Factor of the Single Element Method	52
17	Relationship Between Contrast Temperature and Radiant Contrast Ship Signatures	53

TABLES

<u>Table</u>		<u>Page</u>
1	Convective Cooling Coefficients for Rain Falling on a Vertical Element	15
2	Sky Radiance Tables for Surface Temperature of 10°C	25
3	Ship Temperature for Ship J (1964-71)	36
4	Sky Temperature for Ship J (1964-71)	42
5	Day Contrast Temperature for Ship J (1964-71)	43
6	10 a.m. Contrast Temperature for Ship J (1964-71)	44
7	11 a.m. Contrast Temperature for Ship J (1964-71)	45
8	Noon Contrast Temperature for Ship J (1964-71)	46
9	1 p.m. Contrast Temperature for Ship J (1964-71)	47
10	2 p.m. Contrast Temperature for Ship J (1964-71)	48
11	3 p.m. Contrast Temperature for Ship J (1964-71)	49
12	Night Contrast Temperature for Ship J (1964-71)	50
13	Total Contrast Temperature for Ship J (1964-71)	51
14	Range of Computed Ship Contrast Temperatures	55

I. INTRODUCTION

The Navy has long been interested in the possibility of using infrared sensors to detect and track ships at sea. Furthermore, the threat of anti-ship missiles launched from ships at sea has heightened the Navy interest in passive surveillance methods. The continuing development of detectors, optical materials, and scanning devices has resulted in electro-optical systems for gunnery improvement and passive detection of targets. These early systems established the feasibility of infrared detection and lead to interest in a future program to develop a modular Electro-optical Fire Control Subsystem for present and future naval guns. This would seek to provide passive detection and tracking along with laser illumination for range-finding for targets primarily encountered by ships at sea. The sensor suite for this system includes both a television sensor and a thermal imaging (FLIR) sensor which will operate in the 8-12 micrometer region.

The infrared signatures of surface ships depend upon their construction, operation, and existing weather conditions. The location of power plants, exhaust stacks and areas of different construction causes spacial variations of signature (emitted radiation) over the target. However, to simplify ongoing performance studies, it was decided to approximate the target signature by an average signature which is constant over the target area. This average signature is given as the ship contrast temperature which is the effective temperature difference between the ship and its infrared background. The ship contrast temperatures must include weather effects for system performance studies. In these, the statistical variation of ship contrast temperature with weather conditions provided by weather ship data is first found. These contrast temperatures are then used in the system performance study to determine the percentage of time that the ship target will be detected.

The importance of infrared ship signatures has led to the recent development of computer codes¹ for their calculation. These codes divide a ship into a large number of sections and numerically compute the temperature of each section. The ship temperatures are used to calculate ship radiances. A separate calculation requiring atmospheric temperatures is made to determine the corresponding background radiance. From these, contrast radiance or signature is defined as the sum of the radiance contribution from each ship section minus the background radiance. This

¹Batley, P. E., "Ship Infrared Signatures (SIRS) Computer Model-Technical Overview and User's Manual," NAVSHIPPRANDCEN Rept. SME-78-37 (1978)

²"Fleet Signature Computer Model Program Manual," Westinghouse Defense and Space Center, Baltimore, Maryland, Rept. 8796A, November 1968.

approach results in large, rather slow running computer programs and it would be costly to produce signatures for more than a few days of at-sea weather conditions. The objective of the present work is to compute ship signatures for a large number of weather observations so that the statistical variation of signature including weather effects can be given.

A fast-running approximate method of ship signature computation based on the full-scale codes was developed to utilize the large weather ship data base. Basically, this method approximates a ship by replacing it with a single element and applies 3 correction factors to average the spacial variations. The correction factors are developed for: (1) differences in internal temperatures found throughout the ship; (2) differences in thermal capacity of plating on different sections of the ship; and (3) the presence of a visible stack for exhausting products of combustion. The technique of modeling a ship by a single element and 3 correction factors is termed the Single Element Method. It is designed to be used with weather ship meteorological data. Weather ship data, for ships operating in both the Atlantic and Pacific Oceans were obtained from the Navy Weather Service. These ships provide both surface and upper air data which was taken either hourly or every 3 hours in well-defined locations. This data was used to make hourly calculations of ship contrast temperatures for use in the statistical compilations. The Single Element Method of ship signature calculation reduces computer running time to the point where several years of hourly weather data can be economically run and statistically analyzed.

The purpose of this report is to describe the Single Element Method, its associated computer program, and its application in computing ship contrast temperatures. Ship signatures were calculated for a model of the U.S. Navy Patrol Frigate located at one North Atlantic weather ship location. These will be presented for 8 years of hourly meteorological observations. Statistical results are given for ship, sky, background and ship contrast temperatures. Ship contrast temperatures are specified for day, night and overall operation and for midday hours where they are the largest. Additional computer runs were made to determine the effect of target ship heading on its signature. The methods and results presented herein were developed to aid in present systems performance studies. However, they can be used in providing estimates of ship contrast temperatures for other purposes.

II. BACKGROUND

This section describes the methods previously used to computer ship signatures from which much of the present work will be derived. It will cover signature models and definitions as an aid to understanding the approximate method described in this report. However, this section can be skipped by those readers mainly interested in the statistical results or those already familiar with the previous computer codes. The present work will use the basic models of these codes with the important difference that signatures will be given as a ship contrast temperature instead of as the radiative power induced in a remote sensor. This section will briefly describe these models and give the signature related definitions while also pointing out which parts of the model will be of future use. The infrared Signature of a ship target was originally defined¹ as the signal power it induces in a remote sensor as the sensor's instantaneous field-of-view scans across the ship and its background. This definition is expressed mathematically by the following equation for radiative signal power.

$$P = \iint_{\lambda} (N_t - N_b) \cdot U_a \cdot \tau \cdot d\lambda \cdot d\Omega \quad (1)$$

Here, the signature is really the change in irradiance between instantaneous fields-of-view containing the ship superimposed on its background, N_t , and its background, N_b , respectively. The more general case of the first field-of-view containing the ship plus portions of the background is not covered by equation (1). However, this case will not be considered in the present work which defines the signature as a contrast temperature occurring at the ship and leaves it to the user to relate this to his detector. Furthermore, the detector normalized response and the transmission of the air path between target and detector are not needed in the present analysis of target signature. The difference between the target surface radiance, N_t and the sea surface or background radiance, N_b , defines the spectral radiance contrast at the target. This quantity will be later related to the contrast temperature definition of ship signature.

The target surface radiance is the radiant energy that the target emits due to its surface temperature plus what it reflects from its background. This quantity is given by equation (2) as follows:

$$N_t = R_s \epsilon_s + R_s A_f \cdot (1 - \epsilon_s) + N_b(1 - \epsilon_s) \quad (2)$$

where all radiative quantities are a function of wavelength. The first term in equation (2) is the radiance emitted by the ship's surface which is assumed to be a

¹Ibid, p. 2-2

graybody. That is, this radiance is the product of blackbody radiance at the ship's surface temperature and the emissivity of its surface coating which is assumed to be constant over the waveband of interest. The spectral blackbody radiance is given by the familiar Planck's law as follows:

$$R = \frac{3.74 \times 10^8 \text{ Watts}}{\pi \lambda^5 [\exp(1.439 \times 10^4 / \lambda T) - 1]} \text{ m}^2\text{-Sr} \cdot \mu\text{m} \quad (3)$$

The middle term accounts for the reflection of the sun off of the target and towards the detector. This quantity is governed by the angle factor, A_f , which has been empirically determined to be about 10^{-4} . The sun reflection was found to be only about one percent of the remaining terms in the 8-12 μm waveband hence it was omitted in the approximate method. In the final term, the apparent background radiance, N_q , is the radiance the target receives and subsequently reflects (a portion) from its background. The background seen by a target element can be the sky (upper atmosphere), the air (sea level atmosphere), or the sea depending on the orientation of the element. In the Single Element Method, the element is taken to be vertical and its apparent background is radiance received from a long horizontal air path. This background is represented as a blackbody at sea level air temperature.

Sensor background radiance is the radiant energy felt by a sensor if the target were suddenly removed from its field-of-view. This quantity is composed of radiance from the sea surface plus radiance reflected from the sky (upper atmosphere). Radiance is received from the sky even if it is not in the field-of-view because of reflecting facets caused by sea waves. The sea surface radiance is given by equation (4) as follows,

$$N_b = R_w \epsilon_w + N_s(1 - \epsilon_w) \quad (4)$$

where all radiative quantities are a function of wavelength. The first term in equation (4) is the radiance of the sea surface. The graybody assumption is made so that this quantity can be given by the product of blackbody radiation at the sea surface temperature and the sea surface emissivity which is assumed constant with wavelength. However, it is well-known that water in the infrared (2-15 μm) exhibits a rapid decrease in emissivity⁶ as the angle of incidence is increased above 50° . A curve fit of measured data and theoretical calculations of unpolarized reflections was made to determine the change in effective sea surface emissivity with viewing angle. The following equation results⁷:

$$\epsilon_w = 0.98(1 - (1 - \cos \theta)^5) \quad (5)$$

⁴Kreith, F., "Principles of Heat Transfer," International Textbook Company, Scranton, PA, Second Edition, p. 210, April 1965

⁵Hudson, R. D., Jr., "Infrared System Engineering," John Wiley and Sons, New York, page 35 (1965)

⁶Wolfe, W. L., "Handbook of Military Infrared Technology," Office of Naval Research, Washington, DC, page 167 (1966)

⁷"Fleet Signature Computer Model Program Manual," Op. Cit., p. 5-1

where ϕ is the angle between the line-of-sight from the target to the detector and the normal to the sea surface facets. The determination of sea surface emissivity depends on knowledge of sea waves to predict the angle of the sea surface facets. Surface waves may reflect light from the sky over a wide range of angles. However, Hulburt⁶ concluded from his data that the light reflected by a "breezy sea" comes mainly from a region of the sky that is 25° to 35° above the horizon. Hence, it was concluded that for wind velocities between 5 and 25 knots, the sea facets at the horizon can be represented by smooth water tilted 15° towards the observer. For water surfaces before the horizon the average tilt angle must be reduced to account for negative wave slopes, i.e., waves tilted away from the detector but of sufficiently small slope to allow light to be reflected towards the detector. Experimental data was used to conclude that this reduction in wave slope could be given by half the target-detector elevation angle. The target detector elevation angle is given as 90° minus the target zenith angle, Z_p . The target zenith angle is the angle perpendicular to the sea at the ship and the line-of-sight to the detector. The angles which determine the effective sea surface emissivity are shown in Figure 1.

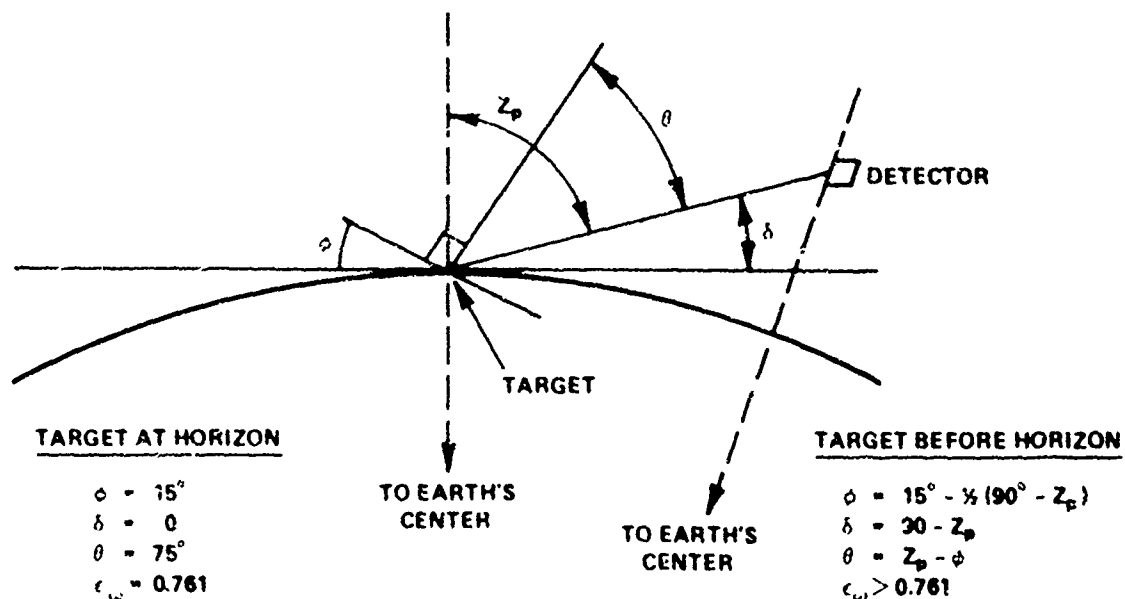


Figure 1. Angles Determining Effective Sea Surface Emissivity

The second term in equation (4) is the radiance reflected by the sea surface facets towards the detector. The sky radiance, N_s , depends on the amount of cloud cover. Hence, it is assumed that sky radiance is composed on the average of a portion from the sky which is clear and a portion from sky that is cloud covered. This is expressed in equation (6) as follows,

$$N_s = (1-f) \cdot N_c + f \cdot S_a \quad (6)$$

⁶Hulburt, E. O., "The Polarization of Light at Sea," J. Opt. Soc. Am., Vol. 24

where all radiative quantities are a function of wavelengths. The fractional part of clear sky, f , is related to the cloud cover which is included in meteorological data. The cloudy sky radiance, N_c , is composed of two parts. The first part is the emission of the cloud, R_c , taken to be a blackbody at the air temperature at the cloud height. This radiance is attenuated by the atmospheric transmission, U_a , of the path between the clouds and the target. The second part is the spectral radiance, S_c , of the atmosphere contained in the path between the clouds and the target. Thus, the cloudy sky radiance, N_c , is the sum $R_c \cdot U_a + S_c$. The clear sky radiative emission, S_a , is the spectral radiance of the atmosphere in a clear path from the target to the top of the atmosphere. The height of the clear sky is arbitrarily taken to be 30 km in calculating clear-sky radiance. The empirical result that most of the sky radiance from a reflecting sea surface comes from a region about 30° above the horizon is used to locate sky radiance. It is assumed that sky radiance is reflected from wave facets at the sea surface which are inclined 15° from the horizontal. This wave slope was modified slightly for targets before the horizon as previously explained. A graphical description of the components of sea surface radiance is given in Figure 2.

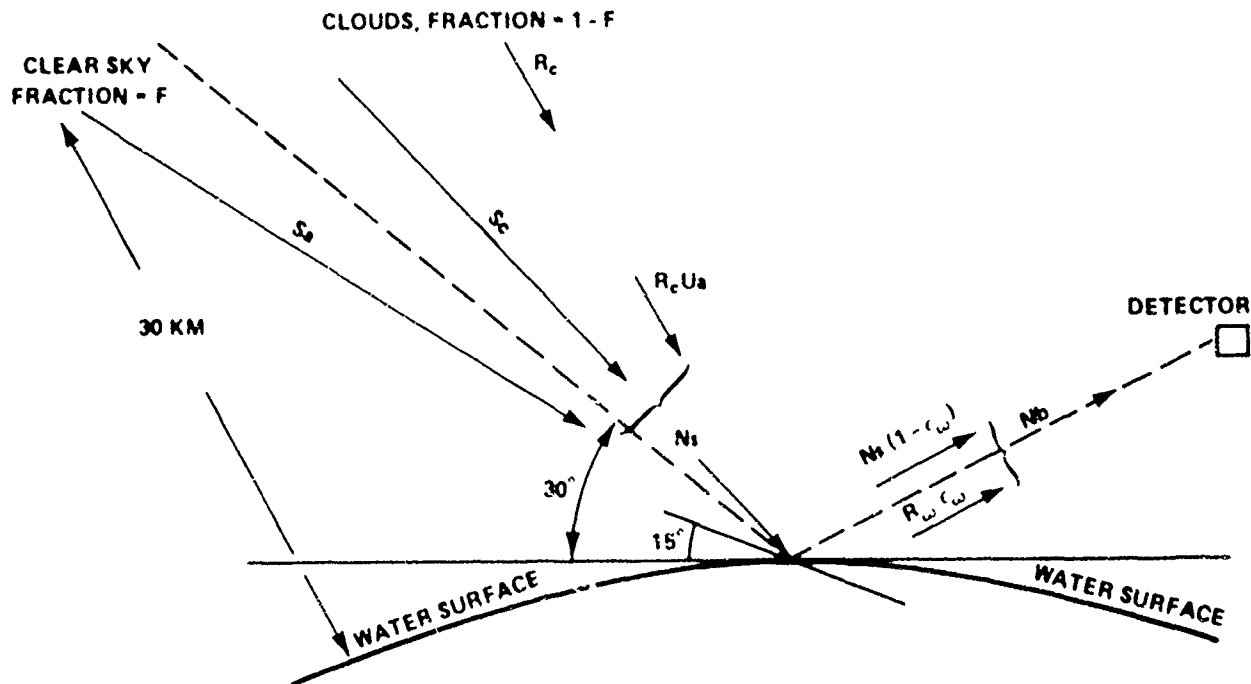


Figure 2. Composition of Sea Surface or Background Radiance

A general equation for the sky reflection angle which takes wave slope into account is derived in the references.⁹ The average sky radiance, defined in

⁹"Fleet Signature Computer Model Program Manual," Op. Cit., p 4-7 to 4-10

equation (6) generally requires a radiance calculation along two paths of different lengths but similar direction. The general equation for the apparent spectral radiance observed from one end of a column of atmospheric gases is given by the following equation.

$$S = \int_0^L U_a \cdot R_a \cdot \epsilon_a \cdot dL \quad (7)$$

This integration is more complicated over paths of changing altitude since all three terms in the integrand vary with altitude. The integral was simplified by a transformation of variables to radiance as the independent variable¹⁰. The new integral was solved numerically using Gauss's quadrature formula in the fifth degree. This formulation requires that air radiance (a blackbody at air temperature) be calculated at five altitudes. In calculating air radiance, the following relationship between air temperature and altitude was assumed.

$$\begin{aligned} H < 11 \text{ km} & \quad T_a = T_o - 72 \quad (^\circ\text{F}) \\ H > 11 \text{ km} & \quad T_a = T_o - 72 \cdot H/11 \quad (^\circ\text{F}) \end{aligned} \quad (8)$$

The spectral radiances defined by equations (2)-(7) were calculated at equally spaced wavelength intervals ($\Delta\lambda = 0.4\mu\text{m}$) in the 8-12 μm region. They were then converted to a band average radiance by simply multiplying by the wavelength interval and summing the spectral quantities.

The optical transmissions along the appropriate air paths are needed in the computation of both clear and cloudy sky radiances. In the 8-12 μm waveband, thermal radiation is attenuated by discrete absorption lines of water vapor, ozone, and a combination of uniformly mixed gases (CO , CO_2 , N_2O , etc.) and by a continuum absorption due to water vapor. Additional energy is absorbed by naturally occurring aerosols which are introduced into the air by continental and surface sources. The present work updated the existing ship signature codes by improving the calculation of atmospheric transmission in the 8-12 μm region. Transmission associated with molecular absorption due to water vapor, ozone and uniformly mixed gases were calculated using tables of absorption coefficient versus wavenumber taken from the LOWTRAN III Computer Code¹¹. Water vapor continuum absorption was calculated from an empirical law¹² derived for the newer III-b version of LOWTRAN. The reduction in transmission due to the presence of aerosols was recently modeled¹³ by combining predictions of marine and continental aerosol particle distributions. The total transmission for a given wavelength is the product of the above individual transmissions.

¹⁰Ibid, p. 4-2

¹¹Selby, J. E. and McClatchey, R. A., "Atmospheric Transmittance from 0.25 to 28.5 μm : Computer Code LOWTRAN 3," Air Force Cambridge Res. Lab., AFCRL-TR-75-0255, May 1975

¹²Selby, J. E., et. al., "Atmospheric Transmittance from 0.25 to 28.5 μm : Supplement LOWTRAN 3B (1976)," Air Force Geophysics Lab., AFGL-TR-76-0258, November 1976

¹³Katz, B. S. and Hepfer, K., "Electro-optics Systems Performance in Selected Marine Environments," Proc. of AGARD Symp. Model. Aerospace Prop. Envir., Ottawa, Canada, April 1978

III. HEAT TRANSFER RATES USED IN SINGLE ELEMENT METHOD

Ship signatures are defined in this report to be the contrast temperature difference between the ship and its infrared background. This section will present methods of calculating the heat transfer rates which produce the temperatures of the Single Element Method. The Single Element Method consists of calculating the temperature in a single element which represents a ship and applying three correction factors to account for differences between the element and the ship. The basic thermal model of this method for predictions of this report is a single vertical plate of unit surface area. This element is heated by solar energy and by internal heat sources such as the power plant or auxiliary machinery. The element is cooled by air flow due to ship and wind motion and by occasional rainfall.

Solar heating is the largest heating rate and is important because it dominates ship temperatures during the day and may influence these temperatures for several hours after sunset. The total solar heat load incident on a given surface is the sum of direct and diffuse solar energy multiplied by the solar absorptivity of its surface coating. The small amount of reflected solar energy due to the albedo of the sea will be neglected. Direct solar radiance is simply the solar constant or solar radiation received outside the atmosphere (1350 watts/m^2) multiplied by the transmittance of solar energy in traversing the atmosphere, i.e.,

$$Q_0 = 1350 U_t \quad (9)$$

The total transmission, U_t , consists of 4 components which account for, (1) absorption of water vapor, (2) molecular scattering, (3) aerosol scattering, and (4) the masking of solar rays by clouds. Equations for these components are given in the references¹⁴. The diffuse or indirect solar radiance is due to the aerosol and molecular scattering of direct solar radiation out of the line-of-sight between the sun and a surface on the earth. It is assumed that half of what is scattered eventually reaches this surface on the average. From this assumption, the following equation for diffuse solar radiance is derived.

$$Q_f = Q_0 (1 - U_{ms} + U_{as})/2 \quad (10)$$

The amount of direct or diffuse solar energy that impinges on a surface depends on the angular relationship between the line-of-sight from surface to sun. This relationship is different for direct and diffuse radiance but both depend on the position of the sun relative to the earth. The sun's location relative to the earth

¹⁴"Fleet Signature Computer Model Program Manual," Op. Cit., p. 6-2, 6-3

is described by the sun's zenith and azimuth angles. The sun's zenith is defined relative to a perpendicular to the earth's surface and its azimuth is defined relative to North. The following equations define the solar zenith and azimuth angles¹⁵.

$$\cos z = (\sin c)(\sin d) + (\cos c)(\cos d)(\cos b) \quad (11)$$

$$\cos Az = \frac{(\cos c)(\sin d) - (\cos d)(\sin c)(\cos b)}{(\sin z)} \quad (12)$$

In these equations, the solar declension, d , is a function of time of the year and the hour angle, b , is 15° for every hour of time away from either side of solar noon. Once the sun has been located, it is only an exercise in geometry to find the direct solar radiance which is given by the component of sunshine normal to the surface. Figure 3 shows the geometrical considerations in determining the normal component of sunshine for a vertical element.

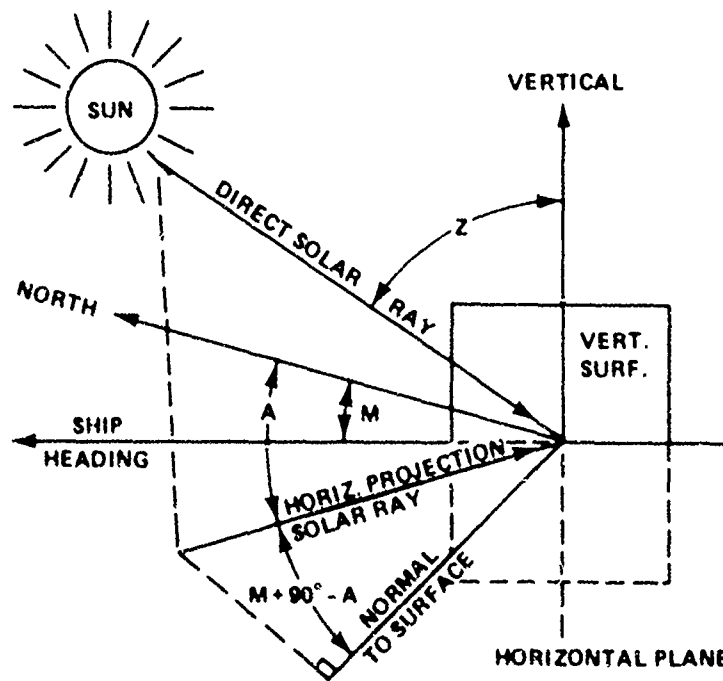


Figure 3. Determination of Direct Solar Radiance on a Vertical Surface

¹⁵Threlkeld, J. L., "Thermal Environmental Engineering," Prentice-Hall, Inc., Englewood Cliffs, New Jersey, p. 319 (1962)

The following equation for direct solar radiance on a vertical element representing a ship of heading, M is derived following Figure 3.

$$Q_d + Q_o \cdot \sin z \cdot \cos(M \cdot 90^\circ - Az) \quad (13)$$

In equation (13), $+90^\circ$ is used for the portside and -90° for the starboard side of the ship. The heading M is measured clockwise (eastward) from north (heading is shown counterclockwise in Figure 3 to avoid cluttering).

The diffuse component of solar radiance is incident on a surface from all directions and is found by integrating the dot product of the surface normal and a distribution function for the intensity of diffuse energy. The following result was derived*

$$Q_i = \frac{Q_f(1 + 2 \cdot \sin z \cdot \cos \frac{1}{2}(M + 90 - Az))}{4} \quad (14)$$

Here, $+90^\circ$ is for a portside element and -90° for a starboard element in agreement with equation (13). In summary, the total solar energy on a vertical surface is given by the following equation

$$Q_s = a(Q_d + Q_i) \quad (15)$$

Heating due to internal sources is described by providing the internal temperature and a convective heat transfer coefficient for each compartment of the ship. These temperatures and coefficients are found in ship design specifications and typical values are chosen for use in the single element method.

Convective cooling rates due to air flow over the ship are generally lower than those due to rainfall but are more important because they always contribute to the ship temperature calculated using weather data. Cooling due to wind is described by a convective coefficient which was derived from measurements made on ships at sea. The following equation results for vertical surfaces**

$$h_a = 3.56 \cdot V^{0.6} \quad (16)$$

Here, V is the relative wind speed which is the vector sum of the wind velocity vector (found in weather data) and the ship's speed and heading vector.

Cooling rates for rainfall are also described by a convective coefficient which was derived for this work using boundary layer analysis. Before proceeding with this analysis, it is necessary to classify rain conditions based on the rate of rainfall. Light rain was defined to be 0.1 in/hr or less and heavy rain 0.3 in/hr or greater in reference¹⁶. The boundary layer analysis was done for each of these rain rates in the following manner, first, it was assumed that these rain

*This equation was derived by Mr. D. Friedman of the Naval Research Laboratory who provided much of the analysis going into the Ship Signature Computer Codes previously mentioned.

**This equation also provided by Mr. D. Friedman

¹⁶"Visible and Infrared Transmission Through Clouds, Fog, and Rain," Raytheon Missile Systems Div., BR-4029, December 30, 1966

rates fall onto and flow along a 3-foot-wide deck and collects on its edge. This forms the initial conditions to a laminar flow boundary layer computer program¹⁷ which calculates the velocity profile for water flowing down a vertical plate. An average velocity is found from the fully-developed velocity profile and this is used to compute an average convective coefficient¹⁸. In these calculations the ship side was taken to be 10 feet in height. Coefficients were found for the maximum light rain and minimum heavy rain conditions assumed above. The minimum heavy rain coefficient was increased 10% and the maximum light rain coefficient was decreased 10% to realize coefficients for representative light and heavy rain. An intermediate value was chosen as a medium rain condition. Many weather conditions occur as drizzle which have less rainfall than light rain. Convective coefficients for drizzles are provided by assuming these are 15% of the corresponding rain values. This arbitrary assumption is based on the fact that free convective coefficients are generally 10-20% of forced convective coefficients. The following table presents the rain coefficients derived for this work.

Table 1. Convective Cooling Coefficients for Rain Falling on a Vertical Element

Intensity	Drizzle	Rain
Light	12 watts/m ² -°C	80 watts/m ² -°C
Medium	20 " "	135 " "
Heavy	30 " "	200 " "

¹⁷Wilson, D. M. and Katz, B. S., "The Use of Water Cooling for Protection Against Thermal Radiation from a Nuclear Weapon Detonation," NOLTR 74-59, 23 Apr 1974
¹⁸Kreith, K., Op. Cit., p. 296

IV. SINGLE ELEMENT METHOD FOR CALCULATION OF SHIP TEMPERATURE

Equations (9)-(16) for heat transfer rates will be used in the Single Element Method to calculate the average temperature of a target ship. In this section, the basic temperature equation and the equations for the 3 correction factors which define this method will be developed. The Single Element Method will be applied to a specific ship, the U.S. Navy Patrol Frigate, and used with weather ship data to calculate contrast temperature differences.

The Single Element Method breaks a ship into sections having common internal temperatures and subsequently into sections having common thermal capacity of outer walls. A basic thermal element is chosen to be a vertical element of unit surface area and the lowest internal temperature, T_{min} , and lowest thermal capacity, W_{min} , of all ship sections. The basic element temperature is calculated and correction factors are derived from the differences of the remaining sections. Correction factors account for the variations in internal temperature and thermal capacity and for the presence of a hot stack. An equation describing the temperature of the basic element is found from a heat balance on this element. This balance, which equates the heat stored in the element to the net heat transferred to it, is given by equation (17).

$$W_{min} \frac{dT}{dt} = Q_s - h_a(T - T_a) - h_r(T - T_a) - h_i(T - T_{min}) \quad (17)$$

Here, W_{min} is the thermal capacity of the basic element which is the product of its density, specific heat, and thickness. Heat conduction rates are not present in equation (17) because the basic element is thermally-thin, i.e., heat is assumed to be uniformly distributed from its front to its rear surface. Also, it is assumed that each section is thermally isolated from its neighbors, i.e., there is no thermal conduction between adjacent elements.

Equation (17) is solved for the basic element temperature by first replacing the derivative, dT/dt by its finite difference equivalent, $\Delta T/\Delta t$. Here, ΔT is the change in element temperature from an initial value, T_o , to a final value, T_b , which results after a time interval, Δt . The following non-dimensional parameters are defined for convenience.

$$HA = \frac{h_a \cdot \Delta t}{W} \quad (18)$$

$$HR = \frac{h_r \cdot \Delta t}{W} \quad (19)$$

$$HI = \frac{h_i \cdot \Delta t}{W} \quad (20)$$

A final grouping of variables has the dimensions of temperature.

$$QS = \frac{QS \cdot \Delta t}{W} \quad (21)$$

The basic element temperature is found by solving equation (17) using the definitions expressed in equations (18)-(21). The result is

$$T_b = \frac{T_o + QS + (HA + HR)T_a + HI \cdot T_n}{1 + HA + HR + HI} \quad (22)$$

Equation (22) is an equation for the stepwise numerical computation of the basic element temperature. That is, this temperature is found from a starting temperature, T_o , a time interval, Δt , and weather data from which the heat transfer rates appearing in equations (18)-(21) can be calculated. The computed temperature, T_b , then becomes the starting temperature for a subsequent calculation based on equation (22) and weather data for the succeeding time interval. Equation (22) provides a stable calculation of temperature regardless of choice of time step. This result was not achieved in the previous ship signature computer programs where a time step of 1/16 hour was typically chosen to avoid stability problems.

The temperature correction factor to account for the different internal temperatures found throughout the ship is developed by subdividing a side of the ship into sections having common internal temperatures. The side of the ship chosen corresponds to the signature while viewing that side. Next, the average or overall ship temperature is the average temperature of all of these sections which have different internal temperatures. This fact is expressed by the following equation.

$$T = \frac{A_1 T_1 + A_2 T_2 + \dots + A_m T_m}{A_1 + A_2 + \dots + A_m} \quad (23)$$

Here, A_i is the area fraction or fraction of the total visible ship surface area which has a temperature, T_i due to the first internal temperature, T_{n1} . A_2 is the fraction of visible surface having a temperature T_2 due to the next internal temperature, T_{n2} , and so forth for a total of m such sections. The sum of the area fractions, $A_1 + A_2 + \dots + A_m$, is 1.0 hence the denominator of equation (22) was included for clarity only. These sections are identical except for their area and internal temperatures hence their individual temperatures can be calculated by equation (22). Equation (22) for calculation of overall section temperature is rewritten below in a form which isolates the internal temperature effect which is to be studied, i.e., let,

$$T_j = D + E \cdot T_{nj} \quad (24)$$

where

$$D = \frac{T_o + QS + (HA + HR)T_a}{1 + HA + HR + HI} \quad (25)$$

$$E = \frac{HI}{1 + HA + HR + HI} \quad (26)$$

and j is an index running from 1 to m (m is the total number of sections). Now,

when equation (24) is substituted in equation (23) for the section temperatures, these are eliminated and the average ship temperature is derived in terms of internal temperatures.

$$T = \underbrace{D + E T_{n_1}}_{\substack{\text{basic} \\ \text{element} \\ \text{temperature}}} + \underbrace{A E (T_{n_2} - T_{n_1}) + \dots + A_n E (T_{n_m} - T_{n_1})}_{\substack{\text{temperature correction factor} \\ \text{for internal temperature variation}}} \quad (27)$$

Equation (27) was designed to divide into a basic element temperature plus some terms depending on area fractions and internal temperature differences of the various ship sections. The first two terms define the average temperature of the entire ship (area fraction = 1.0) if it had internal temperature, T_{n_1} , which is the lowest internal temperature. The remaining terms represent the temperature correction factor for internal temperature variations. An illustration of the calculation of this correction factor will be given later for the Patrol Frigate.

The temperature correction factor to account for the different thermal capacities, W , of outside ship walls are developed in a similar manner but independently of the internal temperature correction method. First, the side of the ship in view is subdivided into a number of sections each having a different thermal capacity. Each of these sections will have a common internal temperature which is the value of the section which has the lowest internal temperature. The average or overall ship temperature for this situation is expressed by the following equation.

$$T = B_1 T_1 + B_2 T_2 + \dots + B_p T_p \quad (28)$$

Here, B_1 is the area fraction having thermal capacity W_1 which results in the overall section temperature T_1 . B_2 is the fraction of visible area having temperature T_2 due to thermal capacity, W_2 , and so forth for a total of p such sections. The individual temperature for each of these sections is also given by equation (22). Equation (22) is rewritten below in a form which isolates the thermal capacity effect to be studied, i.e., let

$$T_j = \frac{T_o + F \cdot V_j}{1 + G \cdot V_j} \quad (29)$$

where

$$V_j = \frac{1}{W_j} \quad (30)$$

$$F = Q_s + (h_a + h_r) T_a + h_i T_{n \min} \quad (31)$$

$$G = h_a + h_r + h_i \quad (32)$$

and j is an index running from 1 to p (p is the total number of sections). Now, if equation (29) is substituted into equation (28) for the section temperatures, these are eliminated and the following equation in terms of variable thermal capacity results.

$$T = \frac{T_o + V F}{1 + V G} + \text{basic element temperature}$$

$$B_2 \left(\frac{(V_2 - V_1)(F - G \cdot T_o)}{1 + G(V_1 + V_2) + G^2 V_1 V_2} \right) + \dots + B_p \left(\frac{(V_p - V_1)(F - G \cdot T_o)}{1 + G(V_1 + V_p) + V_1 V_p G^2} \right) \quad \text{temperature correction factor for thermal capacity variation} \quad (33)$$

Equation (33) was also designed to divide into a basic element temperature plus terms representing the temperature correction factor for thermal capacity variations of the remaining sections. The basic element temperature is the average temperature of the entire ship if it had the thermal capacity function V_1 . V_1 represents the lowest thermal capacity found on ship sections. The temperature correction factors for internal temperature variations [equation (22)] and for thermal capacity variations [equation (33)] were developed independently of each other but both will be added to the basic element temperature to find the overall ship temperature. The justification for doing this is that each correction is small compared to the basic element temperature hence no appreciable error should result when internal temperature and thermal capacities different from basic element values exist simultaneously on some sections. The size of these correction factors will be estimated later for the Patrol Frigate.

The temperature correction factor to account for the presence of one or more hot stacks is developed using the same procedure as in the preceding correction factors. First, the overall ship temperature is taken to be the area fraction multiplied by the overall temperature of the ship without stacks plus a contribution consisting of the area fraction multiplied by the overall temperature of each stack. This first temperature is taken to be the basic element temperature [see equation (22)]. The overall ship temperature is given in the following convenient form by eliminating the area fraction of the ship without stacks from a preceding equation similar to equation (28)

$$T = T_b + C_1(T_1 - T_b) + C_2(T_2 - T_b) + \dots + C_q(T_q - T_b) \quad (34)$$

Here, T_b is the basic element temperature for an area fraction of 1.0 and T_1, T_2, \dots , are average stack temperatures at stack area fractions C_1, C_2, \dots , for a total of q stacks. The average temperature of stacks is given by equation (22) with the important difference that these elements have a high internal heat transfer rate, h_k , and a high internal temperature, T_k , replacing h_i and T_{min} of the basic element. This requires that the internal heating parameter, HI [see equation (20)] be replaced by the stack heating parameter, HK , which is defined as follows:

$$HK = \frac{h_k \cdot \Delta T}{W} \quad (35)$$

The internal temperature, T_n , in equation (22) is replaced by the temperature, T_k , which is the average temperature of flue gases leaving the stack. A temperature correction factor for stack presence can be derived by substituting equation (22) with stack modifications into equation (34) for each stack present. This results in a complex cumbersome equation for stack correction which can be simplified by making the following assumptions. These are: (1) the thermal capacity difference between the stack and basic element is neglected; (2) terms involving the internal

heat transfer coefficient, h_i , will be neglected in expressions involving terms containing the stack heating coefficient, h_k ; and (3) product terms containing h_i will be neglected in expressions which also have product terms containing h_k . These assumptions were justified by calculations based on the Patrol Frigate. Using these assumptions, the following equation for the average ship temperature including the presence of stacks is derived.

$$T = T_b + C_1 \cdot h_{k_1} \left[\frac{(HC + HR + 1)(TK_1 - T_a) - Q_s}{(HC + HR + 1)(HC + HR + h_{k_1})} \right] + \dots + C_q \cdot h_{k_q} \left[\frac{(HC + HR + 1)(TK_q - T_a) - Q_s}{(HC + HR + 1)(HC + HR + h_{k_q})} \right] \quad (36)$$

A final simplification can be made which will allow the stack effect to be rapidly estimated. This is that the contribution to stack temperature by solar heating is likely to be small in comparison to the heat transferred by stack gases. In this case, the solar heating parameter, Q_s , can be neglected in equation (36) which reduces to the following

$$T = T_b + C_1 \cdot \frac{h_k(T_k - T_a)}{(HC + HR + h_k)} \quad (37)$$

Equation (37) is the estimated average temperature of a ship having one stack or several identical stacks and it can be used to initially judge what effect the stacks will have on the total ship signature. The stack correction factor considers the effect of stack gas heating but does not consider the signature contribution of the hot gases (plume) leaving the stack. This is justified in the present work for SEAFIRE systems which operate in the 8-12 μ m waveband where radiance from the predominately carbon dioxide gas in the exhaust plume is rapidly absorbed by the atmosphere. A system operating in the 3-5 μ m waveband would receive radiance from the plume and this would have to be included in the stack correction factor for completeness.

The correction factors for internal temperature differences, thermal capacity differences and for the presence of stacks are given in equations (27), (33), and (36), respectively, along with the basic element temperature, T_b . The single element method for calculating ship temperature consists of taking the average ship temperature to be the basic element temperature, T_b , plus the sum of the 3 correction factors. The basic element temperature is the average temperature of a given plane view of a ship if its entire surface area had the lowest internal temperature and lowest thermal capacity of all major sections of the ship. It should be remembered that an average ship temperature is meaningful in ship signature work only if no hot spots dominate the signature. It will be shown later using the Patrol Frigate Model that internal temperature and thermal capacity differences do not dominate the average temperature calculation. However, large stack internal heat transfer coefficients and high stack gas temperatures do have the potential of contributing as much or more to the signature as the remaining ship for stacks of even relatively small surface area. If this is the case, it makes sense to apply the single element method to the stack alone and neglect the remaining ship surface. It also can be applied to the stacks alone for the case where the main body of the ship is obscured by the horizon. The Single Element Method is applied by using the stack variables in equation (22) while remembering that the resulting temperature applies to the small stack surface area only. The

correction factors do not apply in this case. The stack correction is usually small when signature suppression techniques have been used to cool the exhaust gases or surrounding stack casing. Equation (37) can be used to gauge the stack contribution by using an average value of 5.0 for the sum, "HC+HR," with a time step, Δt , of one hour used in the calculation of HK [see equation (35)].

The single element method requires a ship model for the calculation of the basic element temperature and the 3 correction factors which define the average ship temperature. A model of the U.S. Navy Patrol Frigate was obtained along with the SIRS computer code in which this model was used*. This model breaks the ship into 92 sections and provides the internal temperature and heat transfer coefficient, the thermal capacity, emissivity, absorptivity, surface area, and the orientation of each section. The application of the Patrol Frigate Model in the Single Element Method is given in Appendix A. This appendix shows how the ship is broken into sections for the calculation of internal temperature, and thermal capacity correction factors. Also, the stack is analyzed and the size of its correction factor estimated. The work of Appendix A will later be used with weather ship data in a computer code to calculate the ship contrast temperatures and their statistics.

The equations developed in this section allow the actual ship temperature to be computed. However, for ship signature work, an effective temperature corresponding to the ship radiance is desired. This temperature is defined as the temperature that yields the same radiance in a graybody calculation as the target surface radiance calculated by equation (2). Since sun reflection is neglected and the apparent background is the air, the effective ship temperature is the following

$$T_S = \epsilon_s T + (1 - \epsilon_s) T_a \quad (38)$$

This definition is based on the expectation that the Single Element Method Temperature, T , and the air temperature, T_a , are somewhat the same so that the sum of radiances in Equation (2) is approximately reproduced by the effective ship temperature. However, the emissivity in the 8-12 μ m waveband of Navy Gray paint used with the Patrol Frigate Model is 0.94, hence the effect of the air temperature term is small, thereby lessening the requirement that it be near the ship temperature. The problem of representing sum of radiances with sum of temperatures is discussed in the next section.

*This model, along with the SIRS Computer Program and instructions on its use, was obtained from Mr. R. Burns of the Naval Ship Research and Development Center (Annapolis).

V. CONTRAST TEMPERATURE CALCULATION

The effective ship temperature calculated using the Single Element Method is combined with a background temperature to define the target contrast temperature that is required in SEAFIRE systems analysis. Ship contrast temperature is based on the radiometric definition of ship signature given in Equation (1). That is, the contrast temperature at the target ship is equivalent to the radiant contrast, $N_t - N_b$, which appears in Equation (1). The ship contrast temperature is defined to be the effective ship temperature minus the background temperature as given by the following equation.

$$TC = TS - TG \quad (39)$$

The ship temperature, TS , is the effective temperature which approximately produces the target surface radiance when used in a blackbody calculation for the 8-12 μ m waveband. Background temperature will be similarly defined such that it will approximately produce the background radiance. The background temperature that is analogous to the background radiance defined in Equation (4) is given as follows

$$TG = \epsilon_w \cdot T_w + (1 - \epsilon_w) \cdot T_y \quad (40)$$

Here, T_w and T_y are the sea surface temperature and the effective sky temperature at the appropriate reflection angle. ϵ_w is the sea surface emissivity defined in Equation (5). ϵ_w is about 0.24 for viewing one ship from another. Hence, the background radiance and therefore its effective temperature is composed of about one part water temperature and 3 parts sky temperature. Equation (4) applies to the case where the target ship is slightly before the horizon so that sky radiation will be reflected off of the wave slopes. If the ship were on the horizon, the background would be atmosphere at its sea level temperature. Calculations based on Weather Ship J data showed that sky temperatures range from about -40°C to +10°C while sea temperatures are close to +10°C. It will be shown that the background radiance computed from the background temperature of Equation (40) is not significantly different from the sea surface radiance computed from Equation (4). This was shown by computing radiances by each method and comparing them for sky temperatures between -40°C and 10°C and a water temperature of 10°C. The result of these calculations which were made for the 8-12 μ m waveband are given in Figure 4.

Figure 4 shows a maximum difference of 5 percent between radiances at -40°C and this difference continuously decreases as sky temperature increases. It will be shown later that sky temperatures less than -40°C are rarely encountered and that median sky temperatures are in the 0-5°C region for the weather conditions of this report. Hence, very little error will result from using equation (40) to define the background temperature. The above justification of background temperature depends on defining a sky temperature, T_y , which will reproduce the sky radiance

N_s , which was defined by Equation (6). This is done in a straight forward manner below.

Sky temperature is determined directly from a sky radiance calculation. The sky radiance is composed of clear sky and cloudy sky components whose calculation was previously outlined. Sky radiance for the 8-12 μ m region was found by summing the product of spectral sky radiance given by Equation (6) and a wavelength increment of 0.4 μ m for wavelengths separated by 0.4 μ m in the 8-12 μ m waveband. Sky temperature is defined to be the temperature which yields this radiance in a blackbody calculation made in a like manner. The relationship between temperature and radiance for the blackbody in the 8-12 μ m waveband is shown in Figure 5. Sky temperature could be found by computing the sky radiance and reading the corresponding temperature from Figure 5 whenever a ship signature is required. The previous ship signature codes compute a signature after making a sky radiance calculation. However this procedure will not be used here because sky radiance calculation is a lengthy numerical procedure. This procedure as previously outlined would be prohibitively expensive in computer time for the thousands of contrast temperatures calculated herein using weather data. Instead, sky radiance will be computed beforehand and provided in tabular form to a computer code which calculates contrast temperatures. The development of these tables is described next.

Sky radiance is composed of a clear sky component and a cloudy sky component which depend on the fraction of clear sky, f , as indicated in Equation (6). The calculation of both of these components require that the atmospheric emission over the paths shown in Figure 2 be determined. This requires the calculation atmospheric transmission by the methods given previously. The above review is given to point out that the following inputs are needed in making up the sky radiance tables. These are: (1) A model atmosphere to specify conditions of the atmosphere above sea level; (2) cloud heights to determine the length of cloud radiance paths, and (3) wind speeds which are required in aerosol transmission calculations. The relative humidity is important to transmission due to water vapor and water vapor continuum hence this variable should influence sky radiance calculation. However, it was found that specifying a sea level relative humidity has only a very small effect on sky radiances which are governed by water vapor amounts specified by the model atmospheres. Hence, relative humidity cannot be included in the sky radiance tables until a method of relating sea level and higher altitude relative humidities is developed. Two model atmospheres were chosen in anticipation of the weather data which will be taken from a representative weather ship. This ship, Weather Ship J, operated off the coast of Ireland (Latitude 52°N, Longitude 20°W) hence model atmospheres for a midlatitude summer and a midlatitude winter were chosen from the LOWTRAN transmission work¹³. Five cloud heights and six wind speeds were chosen to cover the range of expected weather conditions. The clear and cloudy sky radiances which make up the sky radiance tables are given in Table 2. The radiances in Table 2 are calculated using a sea level air temperature of 10°C. This value approximates the year-round air temperatures observed by Weather Ship J.

A computer program to compute ship contrast temperature was written using the methods of this report. This program starts with weather ship data and computes ship temperature, sky temperature, background temperature and contrast temperature for many data points. It then computes the probability of occurrence of given values of temperature for all of these ship signature variables. This program was

¹³Selby, R. E. and McClatchey, R. A., Op. Cit.

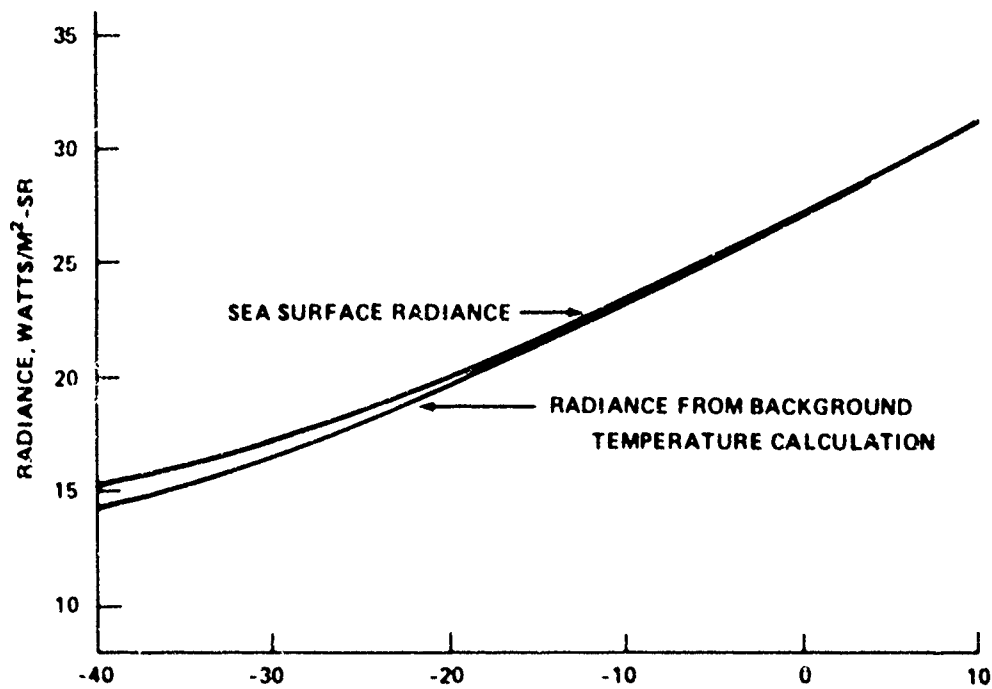


Figure 4. Comparison of Sea Surface Radiance and Radiance Calculated from Background Temperatures for the 8-12 μ m Waveband

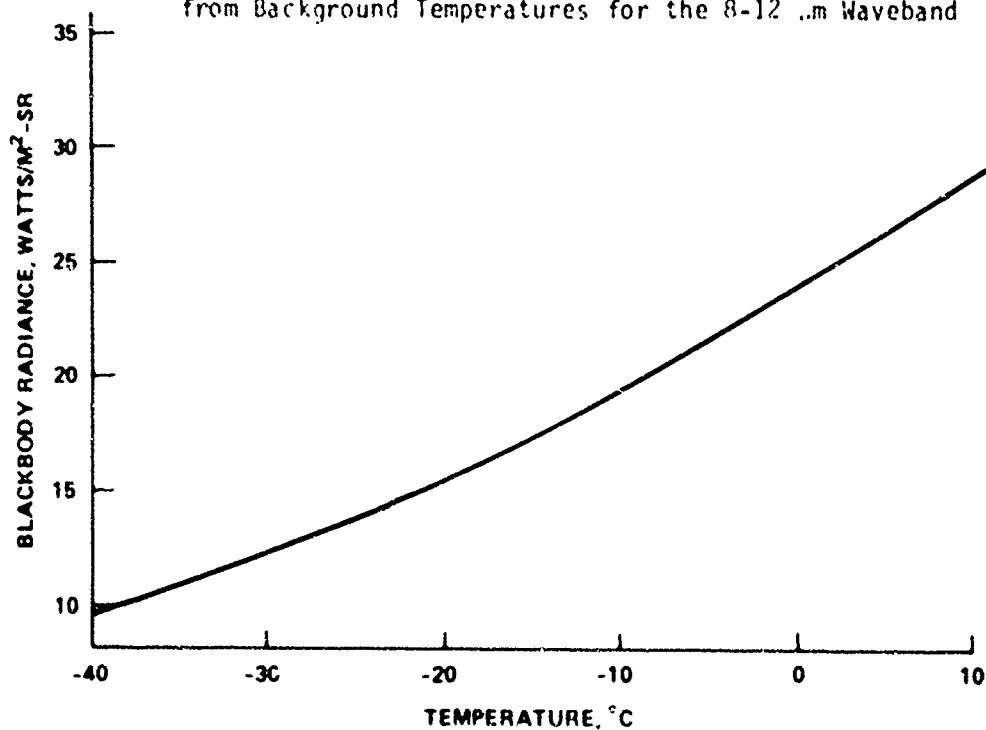


Figure 5. Blackbody Radiance in 8-12 μ m Waveband.

designed to analyze large amounts of data economically with respect to computer running time. For example, six months of hourly weather data is analyzed in 180 seconds of CDC 6500 computer time. This includes calculating and printing data hourly and calculating, printing and plotting the statistical data on a monthly basis.

Table 2. Sky Radiance Tables for Surface Temperature of 10°C.

Wind Speed	Clear Sky*	Cloudy Sky Radiance*				
		H = 1750m	H = 1250m	H = 800m	H = 400m	H = 150m
0.	16.25	26.75	27.78	28.86	29.98	30.78
5.0 m/sec	16.46	26.77	27.80	28.87	29.98	30.78
10.0 m/sec	17.22	26.84	27.94	28.89	29.99	30.78
15.0 m/sec	18.80	27.05	27.98	28.96	30.01	30.78
20.0 m/sec	23.55	27.94	28.56	29.27	30.11	30.80
30.0 m/sec	31.23	30.97	30.97	30.98	30.98	31.04

(a) Midlatitude Summer Model Atmosphere Sky Radiance

Wind Speed	Clear Sky*	Cloudy Sky Radiance*				
		H = 1750m	H = 1250m	H = 800m	H = 400m	H = 150m
0.	8.75	25.77	27.19	28.57	29.89	30.76
5.0 m/sec	9.12	25.80	27.21	28.58	29.89	30.76
10.0 m/sec	10.44	25.90	27.27	28.61	29.90	30.76
15.0 m/sec	13.13	26.19	27.44	28.69	29.92	30.76
20.0 m/sec	20.74	27.36	28.17	29.05	30.02	30.78
30.0 m/sec	31.22	30.95	30.95	30.97	30.96	31.03

(b) Midlatitude Winter Model Atmosphere Sky Radiance.

*Radiance in watts/m² - °C

VI. RESULTS

Data Format

The ASIRCT Computer Program, described in Appendix B, was run with weather data from Weather Ship J to compute contrast temperatures using the method of this report. These temperatures were analyzed statistically to find cumulative probabilities of occurrence of temperature which was the form required for SEAFIRE systems analysis. The contrast temperatures reported are for the 8-12 μ m region of the infrared since the SEAFIRE systems as well as most present modular FLIR systems operate in this waveband. Ship, sky and background temperature are the component temperatures which define the contrast temperatures. These are computed to aid understanding of contrast temperature results and to tie in the contrast temperature and contrast radiance definitions of ship signature. All calculations were made using the model of the U.S. Navy Patrol Frigate which is given in Appendix A. It was also shown in Appendix A that results computed using this model will provide a good approximation for all similarly constructed ships having cooled stacks. The results of contrast and component temperatures will be presented for 8 years of Weather Ship J operation. These temperatures are given primarily for a target ship heading which results in a maximum contrast (due east or west). However, contrast temperatures for other headings will be given and the effect of heading on contrast will be discussed. This section will also provide the rationale for defining probabilities and results will be given in terms of these probabilities. A method of relating the ship contrast temperature and ship radiance signature will also be given. Finally, ship contrast temperatures will be given for a background consisting of air at sea level temperature. This case might be expected for a target ship slightly above the horizon where there is no reflection from the sea in the background.

Statistical analysis of temperatures calculated in this report consists of finding the cumulative probability of occurrence of all temperatures that are equal to or less than a given value. This definition is useful in system studies where a given system is assumed to be operational at a given contrast temperature. Then, the probability of system success is equal to the probability that the contrast temperature is above the critical value. The results are produced by compiling the individually computed ship contrast temperatures into a number of standard temperature values. The standard values are provided in a list of temperatures separated by a 0.2°C interval between -3.0°C and slightly larger intervals outside this range. This list can be found in Figure B-2 which is a listing of the ASIRCT computer program (see TLIST). A computed temperature is compared sequentially to this list until the first smaller temperature is encountered. The computed temperature is stored at this list temperature. This process is repeated for many calculated temperatures until a large number of points have been stored in various positions on the standard list. A probability density function for ship temperature is produced by dividing the number in each temperature of the list by the total number of temperatures stored. The probability that temperature is equal to or lower than the listed temperature is computed sequentially by use of the probability

density function starting with the highest temperature. Calculation is continued until probabilities for all temperatures in the standard list have been computed. These cumulative probabilities are printed as tables in the computer output for each of the contrast and component temperatures mentioned in this report. However, to simplify the presentation of data, temperatures corresponding to standard probabilities from 0.10 to 0.95 were computed by interpolating the computer printed tables. The standard probabilities and their corresponding temperatures were also printed in the computer output and are reproduced in this report.

Ship Heading and Solar Insolation

The ship's heading influences the amount of solar energy absorbed on a vertical element (see Figure 3 and equations (13)-(15)). It has a significant effect on daytime signatures since solar heating is a major factor in raising the bulk ship temperature above its ambient air temperature value. Daytime contrast temperatures are very important in SEAFIRE systems studies where FLIR systems are compared to television systems for passive daytime operation. Solar insolation is the rate of heating received at the earth from the sun hence an element aligned perpendicularly to the line-of-sight to the sun receives the maximum possible heating. The line-of-sight from earth to sun also depends on the time of year due to the variation in the sun's declination. Hence, the heating of a ship which is represented by a vertical element depends on the orientation of the element with respect to the line-of-sight to the sun. The maximum solar insolation occurs on June 21 when the sun's declination is a maximum and minimum insolation occurs on December 21. The sun rises in the east and traverses the southern sky in a westward direction. Hence, a ship heading due east will receive maximum or all day direct heating on its starboard side and a ship heading due west will receive maximum heating on its portside. Ships heading due south (starboard) or due north will receive direct solar heating in the morning and afternoon, respectively, and indirect or diffuse solar heating the remaining time when its sides are shaded. Ships heading due west (starboard) or due east (portside) are always shaded hence receive diffuse solar heating only. These 3 headings for an element on the starboard side, due east, due south, and due west, which have full, half, and no direct solar heating will provide the reference headings for this report. The daily incident solar energy on a starboard vertical element for each of these headings was computed by summing hourly the direct and indirect heating rates given by equations (13) and (14). These are shown in Figure 6 for the 52°N longitude of Weather Ship J. Figure 6 shows that a factor of 3 or more difference in daily incident solar energy exists between the minimum (270° heading) and maximum (90° heading) values. The dip in solar heating received by the vertical element when solar insolation is a maximum (June 21) is due to the relatively large angle between the perpendicular of the element and the line-of-sight to the sun. Contrast temperature calculations given later will show that solar heating differences are important to daytime contrast temperatures. However, the bulk of the contrast temperature calculations of this report are for the heading producing maximum solar heating (90°).

Temporal Division of Data

The variation of incident solar heating with time of the year suggests breaking the year into seasons. Three seasons were defined. These are: (1) a winter season, January, February, November and December having minimum solar heating; (2) a spring-fall season, March, April, September and October having intermediate solar heating; and (3) a summer season, May, June, July and August having maximum solar heating. Solar heating is seen to decrease in Figure 6 over the summer month for the due east heading due to a loss in angular efficiency caused

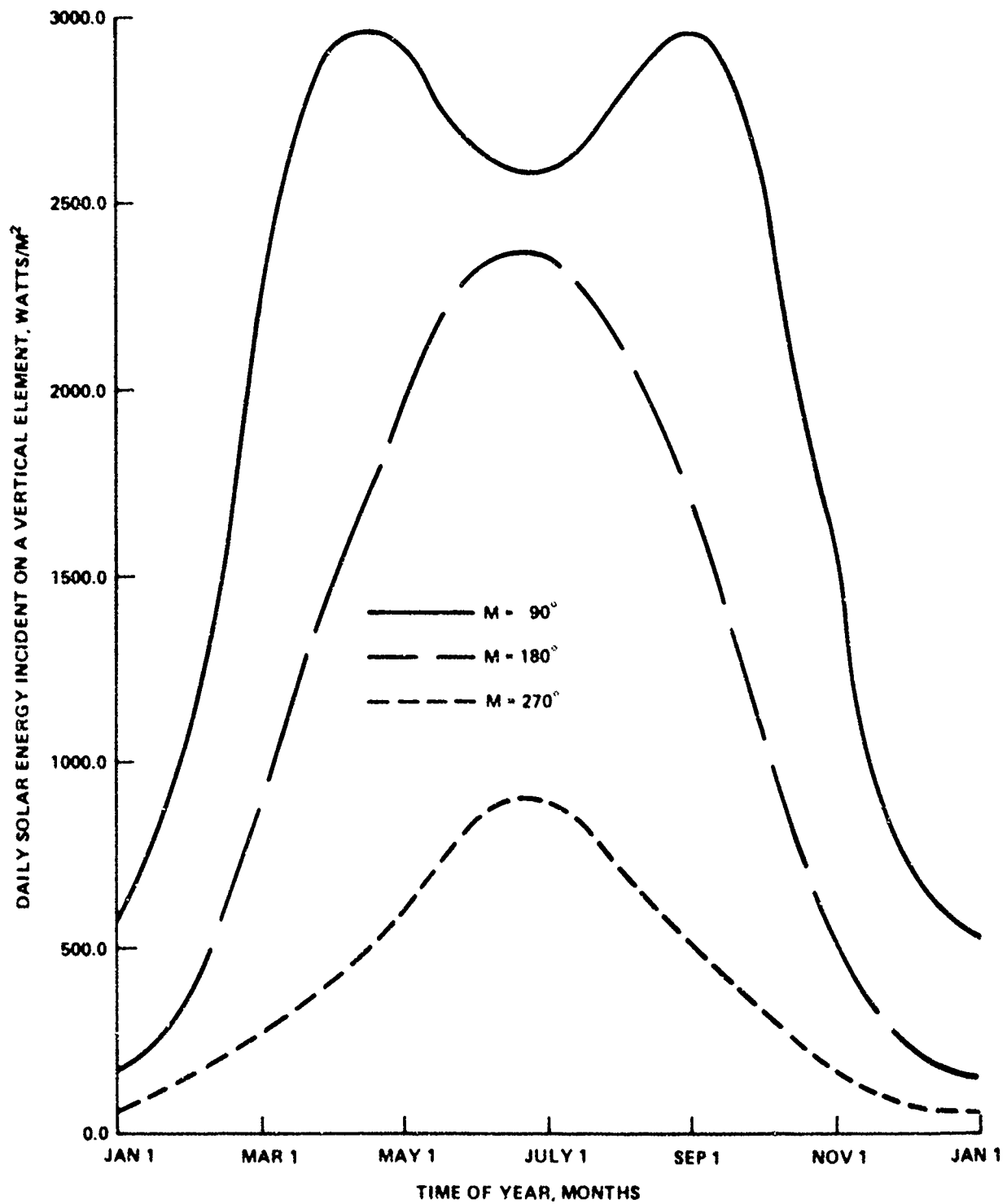


Figure 6. Incident Solar Energy on a Vertical Element for Various Ship Headings at Longitude 52°N

by high solar altitude angles. But, even here there is a characteristic difference between the summer and spring-fall seasons even though their total solar heating is about the same. That is, the spring-fall season has higher mid-day heating due to the better angular alignment between the sun and the vertical element. It will be shown that this will result in significantly higher daytime contrast temperatures.

Ship contrast and its component temperatures were computed using data gathered by Weather Ship J during the years 1964-71. These will initially be presented and discussed for the due east ship heading and for the 3 seasons defined above. Subsequently, representative results will be given for the due south and due west headings shown in Figure 6. For the due east heading, tables of the standard probabilities will be given for each temperature, each season, and each of the 8 years. A representative average value of the 8 years will be plotted for each season and for each temperature.

Effective Ship Temperature Definition

The effective ship temperature is defined to be a thermodynamic measure of the ship target surface radiance. It is the temperature of a blackbody [equation (3)] that radiates the same amount of energy in the 8-12.μm region as that calculated by summing the radiation emitted and reflected from components of the ship's structure. The reflected component is from surrounding air at its sea level temperature. This effective ship temperature was given by equation (38) in terms of the actual ship temperature, T , and the apparent background air temperature, T_a . The actual ship temperature is calculated by the Single Element Method developed in Section III. Calculated effective ship temperatures are given in Table 3 for the years 1964-71 and the 3 seasons. Table 3 lists the standard probabilities. For example, a temperature of 25°C at a probability of 0.90 means that 90 percent of all calculated temperatures are 25°C or lower. Representative effective ship temperatures are given in Table 3 and are shown in Figure 7.

In this and in future graphs and tables, representative values are defined to be the average of the highest and the lowest values of 8 yearly temperatures given in the tables. Figure 7 indicates that the effective ship temperatures are generally highest in the summer and lowest in the winter as might be expected. However a closer examination of Table 3 shows that some spring-fall temperatures are higher than their corresponding summer values. This occurs at higher ship temperatures which correspond to mid-day hours where spring-fall solar heating rates are the larger. Also, the fact that more spring-fall temperatures are not noticeably higher is explained by an analysis of the weather data which shows that wind speeds are about 15 percent lower in the summer than in the spring-fall. High wind speeds are especially effective in reducing the high ship temperatures.

Background Temperatures

The background temperature was defined to be a thermodynamic measure of the sea surface radiance. The use of the sea surface radiance as the background is a consequence of the receiver-target geometry chosen for this study, i.e., a ship at or near the horizon. This background was defined in equation (40) as intrinsically derivable from a mixture of sky and sea radiances. The weather data show that sea temperature is always within a few degrees centigrade of 10°C. But sky temperature which depends on cloud conditions in addition to air temperature varies widely daily and will also depend on season of the year. Sky temperature calculation is handicapped by the availability of only two model atmospheres, one for summer and one for winter. This causes a discontinuity in the clear sky component when going

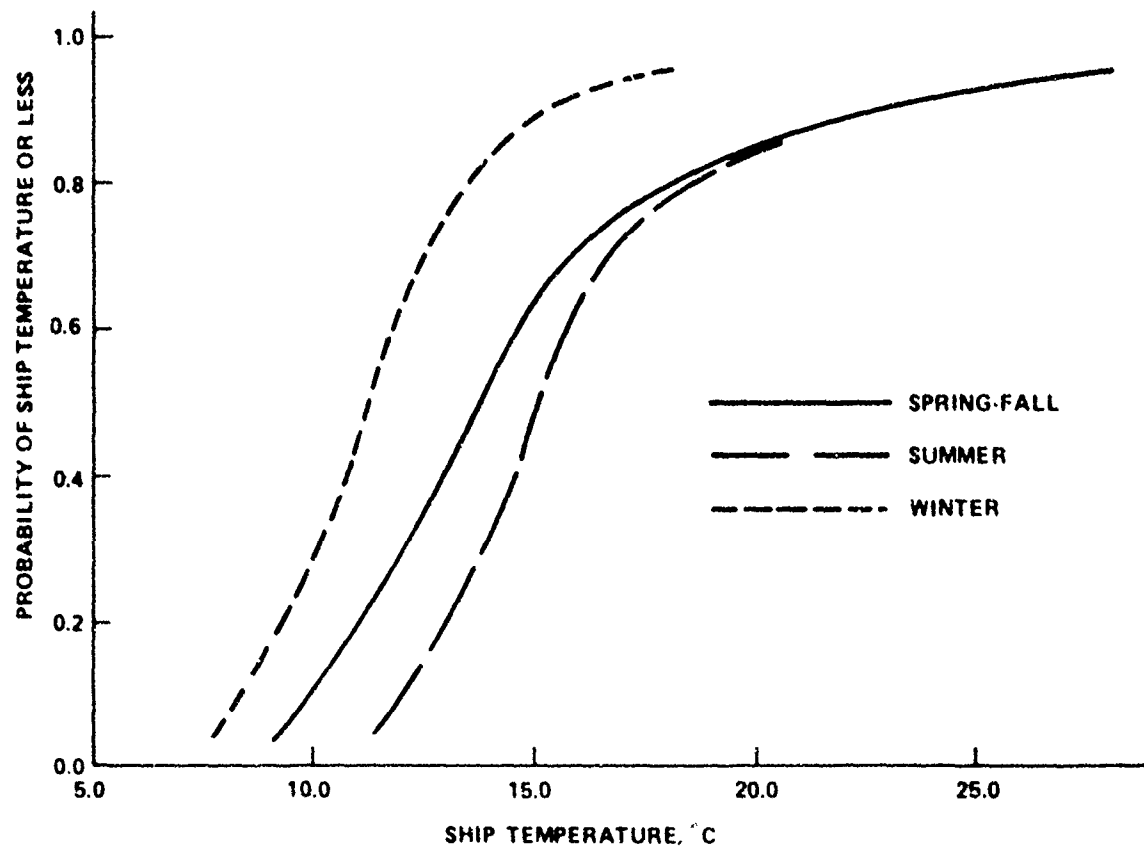


Figure 7. Probability of Observing Effective Ship Temperature

from one model to the other. That is, the Midlatitude Winter Model predicts about -40°C and the Midlatitude Summer about -20°C for the clear sky component of temperature. Fortunately, it was found that sky temperatures in this report are largely governed by its cloudy sky component because of the preponderance of cloudy skies encountered. That is, an analysis of the weather data showed that median cloud covers are 90 percent or more for each season. Cloudy sky radiances and hence temperatures are only slightly influenced by choice of model atmosphere because sea level temperatures are taken from the weather data and air temperatures supplied by the model are used for low altitudes only (median cloud heights less than 1 km). These low altitude air temperatures do not vary much with season. Probabilities of sky temperatures calculated using the Weather Ship J data are given in Table 4 for the years 1964-71 and the 3 seasons. Representative values of sky temperature are also shown in Figure 8 for each season.

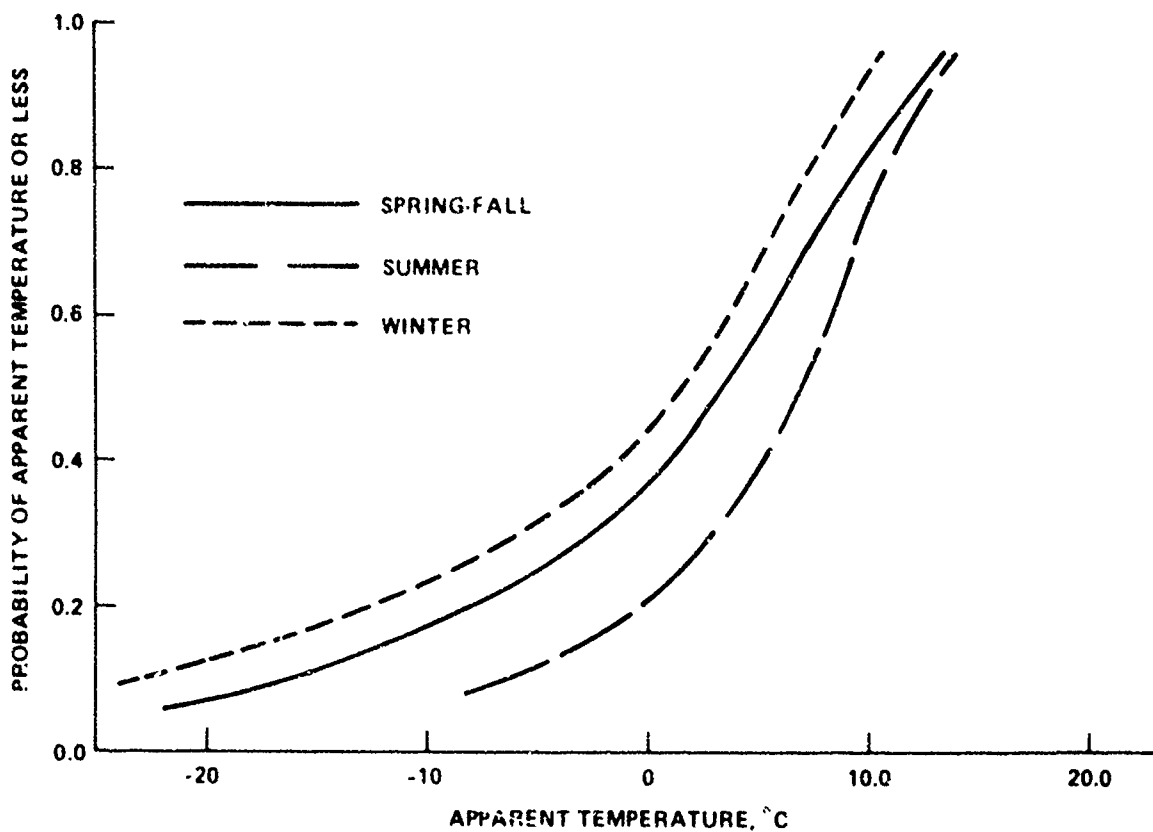


Figure 8. Probability of Observing Reflected Sky Temperature

Table 4 and Figure 8 show that summer sky temperatures are the warmest and winter the coldest as was expected. Most of the variation of sky temperature with season is due to differences in air temperature near sea level because of the low clouds. This difference is only about 5°C between winter and summer seasons. However, the lower sky temperatures show the influence of some relatively clear skies and here there is a much larger difference between winter and summer sky temperature. The spring-fall season contains two months in each model atmosphere hence it has intermediate sky temperatures in the low temperature region which is influenced by the choice of model atmosphere.

Background temperatures are computed by adding the sea temperature component to the sky temperature. These were calculated for a representative year (1966) and the cumulative statistics are shown in Figure 9 for the 3 seasons. Background temperatures are not given in the tables because their calculation was not printed in the ASIRCT computer program output when the 8 years of weather data were run. The background temperature consists of approximately 1 part sky temperature and 3 parts sea temperature for viewing one ship from another. Hence, the background temperatures have less variability than the sky temperature because sea temperatures vary little with season. The fact that sea temperatures are warmer in summer contributes to the larger summer background temperatures.

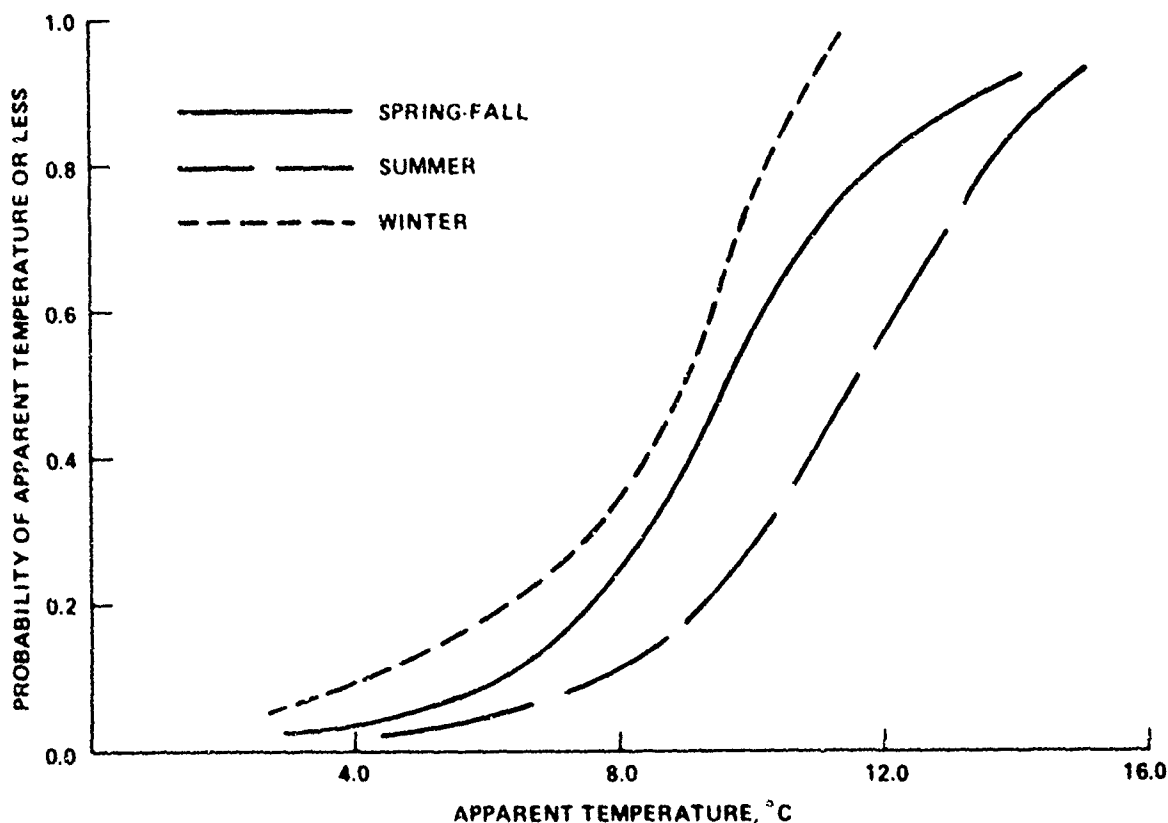


Figure 9. Representative Probability of Observing Background Temperature

Ship Signatures - Contrast Temperatures

The ship contrast temperature was defined to be simply the effective ship temperature minus the background temperature [see equation (39)]. A zero contrast temperature is associated with zero radiance difference between the ship structure and the combined air-sea background. Contrast temperatures were computed by the ASIRT computer program for daytime, nighttime and total time of operation.

Daytime Contrast Temperatures

Daytime contrast temperatures were computed for all daylight hours and for the mid-day hours between 10 a.m. and 3 p.m. Cumulative probabilities of daytime contrast temperatures are given in Table 5 for the years 1964-71 and for the three seasons. Representative values of daytime contrast temperature which appear in Table 5 are also plotted in Figure 10 for each season.

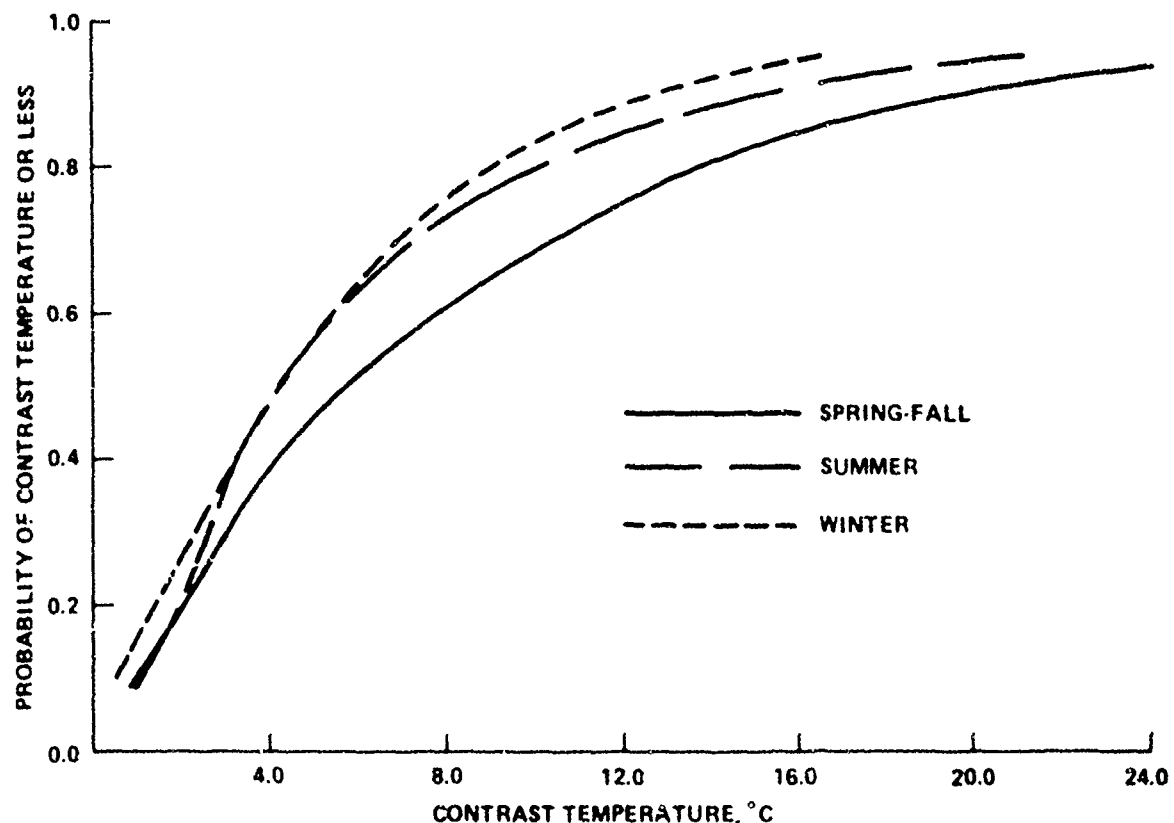


Figure 10. Probability of Observing Daytime Contrast Temperatures

Figure 10 and Table 5 show that statistically the differences between winter and summer daytime contrast temperatures are not large if the contrast temperatures are less than about 10°C. This closeness can be explained by comparing the ship temperatures plotted in Figure 9. There, it is seen that the difference between summer and winter temperatures is about the same (within 0.5°C) for 80% of

the time. Thus, the near agreement of summer and winter contrast temperatures is largely a fortuitous combination of ship and background temperatures. It will be shown that the agreement in contrast temperature is caused by similar early morning and later afternoon values where solar heating effects are minimized due to the unfavorable angular position of the sun. The spring-fall daytime contrast temperatures are significantly larger than the other seasons due to the relatively larger ship temperatures and relatively low background temperatures. That is, the solar heating is maximized as a consequence of favorable solar altitude angles while the background radiance and therefore the effective background temperature is reduced by the smaller probability of cloud cover. High spring-fall and summer contrast temperatures are evident in the mid-day calculations. These are given in Tables 6-11 for the hours 10 a.m. to 3 p.m., the years 1964-71 and the 3 seasons. Representative average values are given in each table and these are plotted in Figure 11 for the maximum daytime contrast temperatures and the 3 seasons. The maximum temperatures are found to occur at 1 p.m.

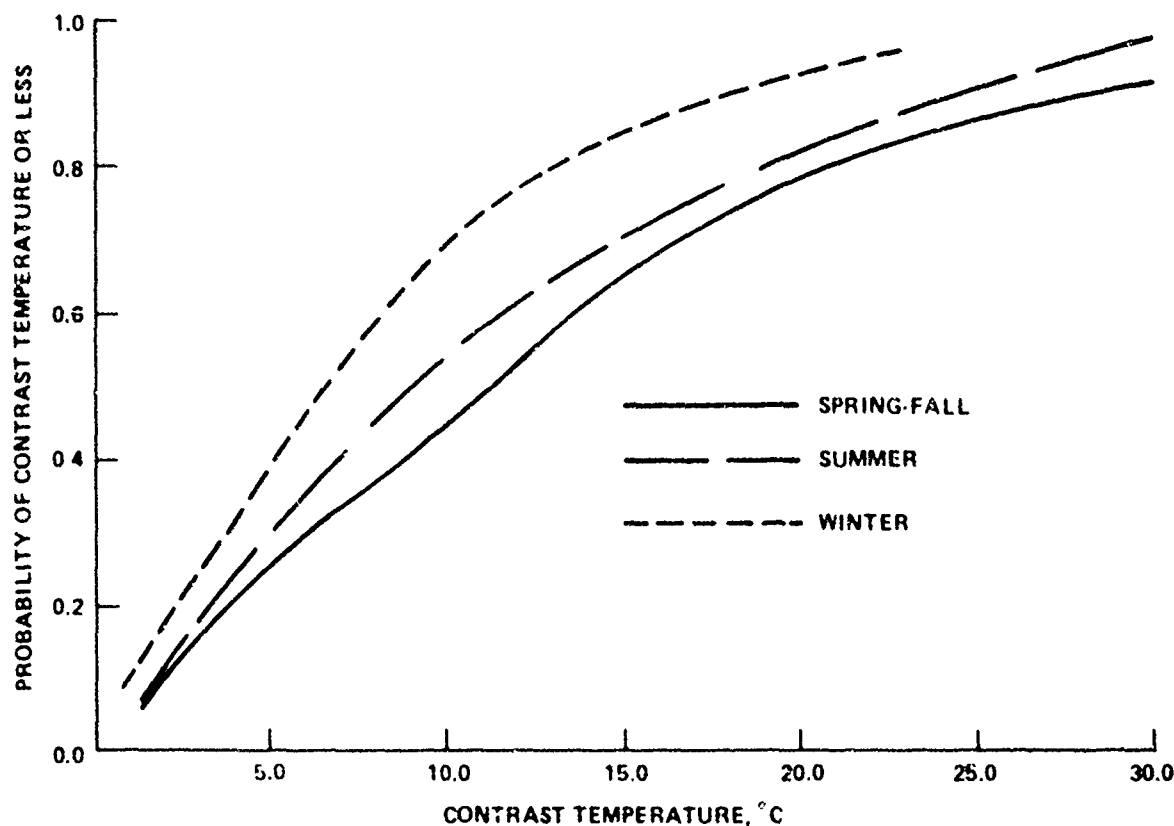


Figure 11. Probability of Observing Maximum Contrast Temperatures

Figure 11 and Tables 6-11 show that the mid-day contrast temperatures are the highest in the spring-fall season due primarily to the more favorable solar altitude angles. However, this data also shows that the mid-day summer contrast temperatures are significantly higher than the corresponding winter values. These higher mid-day contrasts of summer are not obvious in Figure 10 which showed similar

winter and summer overall daytime contrasts. Hence, it can be concluded that it is the early morning and later afternoon contrast temperatures which are similar in winter and summer. The mid-day contrast temperatures are the highest temperatures occurring in Figure 10 and these are seen to be higher in summer. Mid-day contrasts are significantly larger in summer than winter due to the relatively larger ship temperatures. These can be seen in Figure 7 which shows that the difference between summer and winter ship temperatures increases dramatically for probabilities greater than 0.8.

Nighttime Contrast Temperatures

Cumulative probability of contrast temperature for nighttime operation are given in Table 12 for the years 1964-71 and the 3 seasons. Representative values of nighttime contrast temperatures appear in Table 12 and are also plotted in Figure 12 for the 3 seasons.

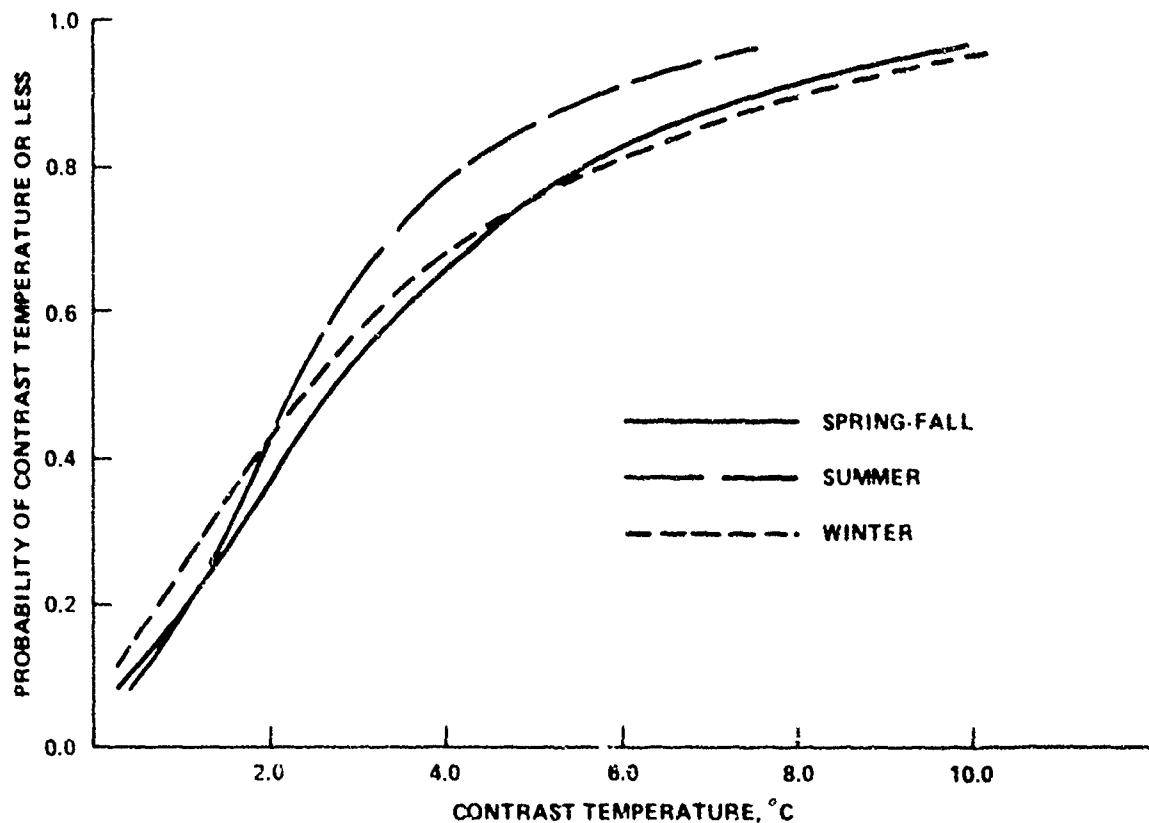


Figure 12. Probability of Observing Nighttime Contrast Temperatures

Figure 12 shows that nighttime contrast temperatures are about a factor of 2 lower than daytime values and have less variability between seasons. These facts show the importance of solar heating in enhancing daytime FLIR performance. It may be surprising that summer nighttime contrasts are generally the lowest. This behavior is due to the relatively high summer background temperatures without offsetting high ship temperatures.

TABLE 3 SHIP TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	17.28	15.99	19.49	17.91	18.98	17.27	19.38	18.98	17.74
.90	14.97	14.30	16.23	15.13	15.54	14.54	15.71	15.48	15.27
.80	12.74	12.90	13.61	13.42	13.36	12.82	13.58	13.92	13.37
.70	12.98	12.32	12.71	12.72	12.61	11.92	12.33	13.01	12.47
.60	12.44	11.74	12.02	12.24	12.00	11.19	11.58	12.41	11.82
.50	11.91	11.18	11.51	11.73	11.48	10.54	10.93	11.82	11.23
.40	11.43	10.66	11.01	11.19	10.96	9.90	10.36	11.27	10.62
.30	10.92	10.17	10.45	10.62	10.46	9.17	9.76	10.64	10.05
.20	10.14	9.66	9.86	10.04	9.93	8.36	9.15	9.89	9.25
.10	9.50	8.97	9.04	9.22	8.87	7.31	8.30	8.84	8.41

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	28.15	30.54	28.35	25.87	28.08	26.92	24.86	28.44	27.70
.90	22.81	24.82	22.68	21.21	22.24	22.46	20.52	23.06	22.67
.80	17.88	18.26	17.64	16.45	17.02	17.61	16.93	17.84	17.36
.70	16.18	15.70	15.66	14.92	15.05	15.52	15.40	16.70	15.81
.60	14.85	14.72	14.62	13.73	14.42	14.48	14.48	15.62	14.68
.50	13.82	13.95	13.60	12.89	13.72	13.69	13.58	14.61	13.75
.40	12.74	13.10	12.68	12.28	12.78	12.96	12.60	13.45	12.87
.30	11.76	12.15	11.87	11.65	11.76	12.02	11.68	12.25	12.01
.20	10.95	11.34	11.15	11.02	10.66	11.34	10.79	11.36	11.01
.10	9.95	10.25	10.32	9.69	9.32	10.47	9.76	10.26	9.90

SPRING-FALL (MAR., APR., SEPT., OCT)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	26.63	28.38	28.82	27.09	28.41	26.09	25.70	26.68	27.26
.90	22.56	23.53	23.33	22.66	23.47	22.14	21.77	22.67	22.65
.80	18.12	19.49	18.89	18.41	19.28	17.85	17.83	18.75	18.66
.70	16.91	17.38	17.07	16.55	17.46	15.86	16.51	17.11	16.62
.60	15.88	16.13	15.89	15.53	16.49	15.13	15.50	15.98	15.81
.50	15.30	15.55	15.14	14.87	15.51	14.55	14.72	15.37	15.06
.40	14.67	15.06	14.41	14.34	14.44	14.01	14.02	14.66	14.54
.30	13.95	14.34	13.61	13.74	13.46	13.42	13.34	13.77	13.64
.20	12.87	13.53	12.70	13.02	12.65	12.74	12.58	12.78	12.06
.10	11.58	12.58	11.62	11.31	11.77	11.71	11.54	11.77	11.95

SUMMER (MAY, JUNE, JULY, AUG.)

Ship data exhibit large amounts of cloud cover which effects both the daytime ship temperatures and all background temperatures. Hence, these contrast temperatures may show more variation with season in a more cloud-free location.

It was previously stated that target ship heading controls the contrast temperature of a ship target because its solar heating depends on its heading. Further, Figure 6 defined 3 basic headings depending on whether the vertical element receives direct solar heat all, one-half or none of the time. The ASIRCT computer program was run for the 3 basic headings and a representative year (1966). It was found that the daytime contrast temperatures are very sensitive to heading due to the great differences in incident solar heating as shown in Figure 6. These are shown in Figure 14 for the 3 seasons. Figure 14 shows that there is about a factor of 2 difference in daytime contrast temperature between a due east (90°) and a due west (270°) heading for the starboard vertical element. Also, the coincidence of some winter and summer daytime contrast temperature observed in Figure 10 for the due east heading is not present in the remaining headings. Daytime contrast temperatures for the due south and due west headings show spring-fall values are the largest in agreement with the results found for the due east heading. This result remains true due to the relatively lower background temperatures calculated in the spring-fall season (see Figure 9). The maximum (1 p.m.) contrast temperatures show an even greater dependence on heading than the overall daytime contrasts. Here, the due south heading has maximum contrast temperatures which are about 40% of the due east heading when probabilities of observing contrast temperatures or less are compared. This drops to about 30% for comparing due west to the due east heading. The night contrast temperatures are nearly the same for the various headings although the due east contrasts are slightly higher (e.g., 0.25-0.50 C) due to the lasting effect of solar heating. An interesting observation is that the daytime contrast temperatures for the due west heading are nearly equal to the nighttime contrast temperatures seen in Figure 12 and Table 12. Thus, the relatively low, totally diffuse solar energy received in this heading and at this location is almost totally ineffective in building daytime contrast temperatures.

Signatures with Air Backgrounds

The previously given contrast temperatures calculations assume that the background of the target ship consist of radiant emission from the sea and reflected radiance from the sky and off of the sea surface wave slopes. In this background model, the target must be slightly before the horizon so that no radiance from an air path along the line-of-sight to the target but behind it appears in the background. If part of the ship is above the horizon, radiance from this air path will contribute to the background. Contrast temperatures were calculated for backgrounds consisting of sea level air temperature only. This is the limiting case where the target ship is at or slightly over horizon and no sea emission or sky reflection reaches the infrared detector. In the general case of a ship near the horizon, the background radiance will be generally less than the all air emission but greater than the all sea emission plus sky reflection case. This is due to the fact that the apparent temperature of the sky is sometimes quite cold (see Figure 8) and is always less than the sea level air temperature.

Contrast temperatures for backgrounds consisting of sea level air are given in Figure 15. Figure 15 presents the night, day and total contrast temperature for each of the three seasons and weather data taken by Ship J in 1966. This figure shows much smaller ship contrast temperatures in comparison with those having a sea surface background (see Figures 10-13). Night contrast temperatures are especially reduced and do not vary significantly with season. Nighttime contrasts are low

Total Contrast Temperature

The daytime and nighttime contrast temperatures were combined to yield total contrast temperatures based on 24 hours a day operation. These are given in Table 13 for the years 1964-71 and the 3 seasons. Representative average values from Table 13 are shown in Figure 12 for the 3 seasons.

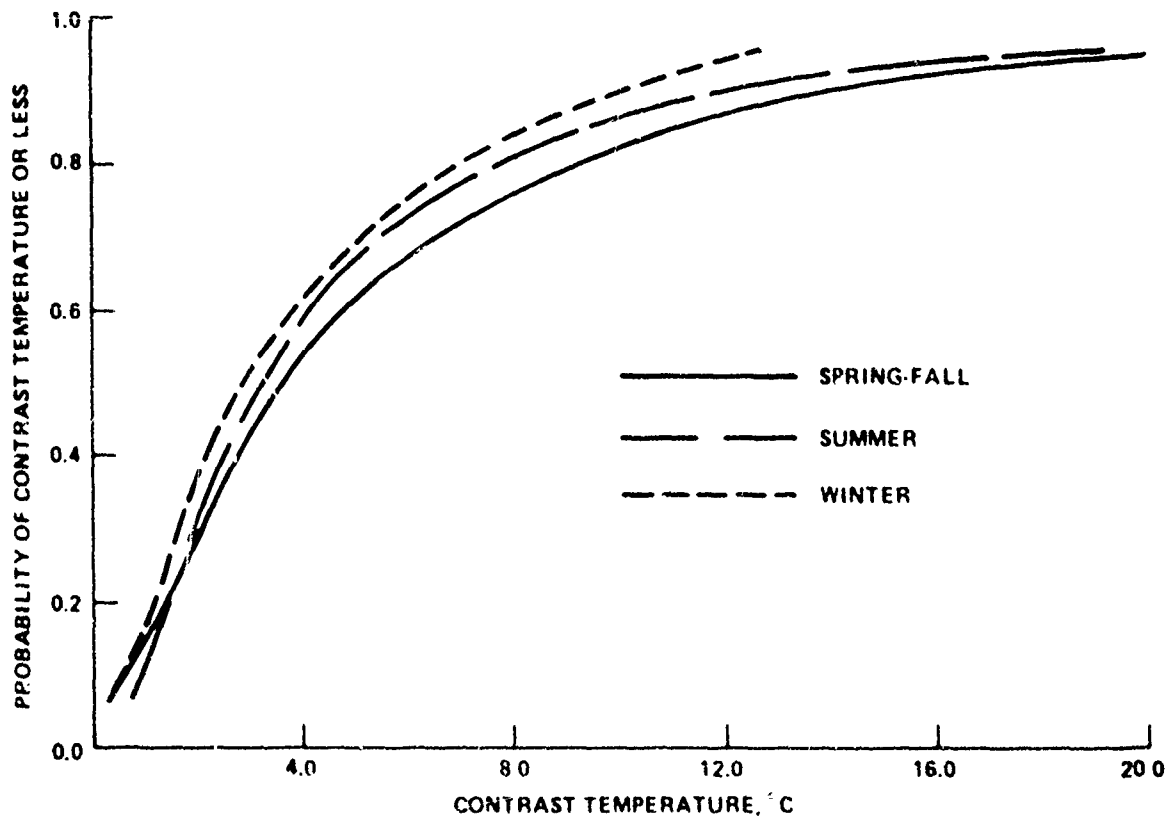


Figure 13. Probability of Observing Total Contrast Temperatures

Figure and Table 13 show that the total contrast temperatures do not vary significantly with season. This is understandable from the previous results where it was shown that only the mid-day contrast temperatures show large seasonal differences due primarily to differences in received solar heating. Since the mid-day hours occur only 25% of each day, their effect is largely lost in the cumulative distributions of Figure 13. However, it should be remembered that the Weather Ship

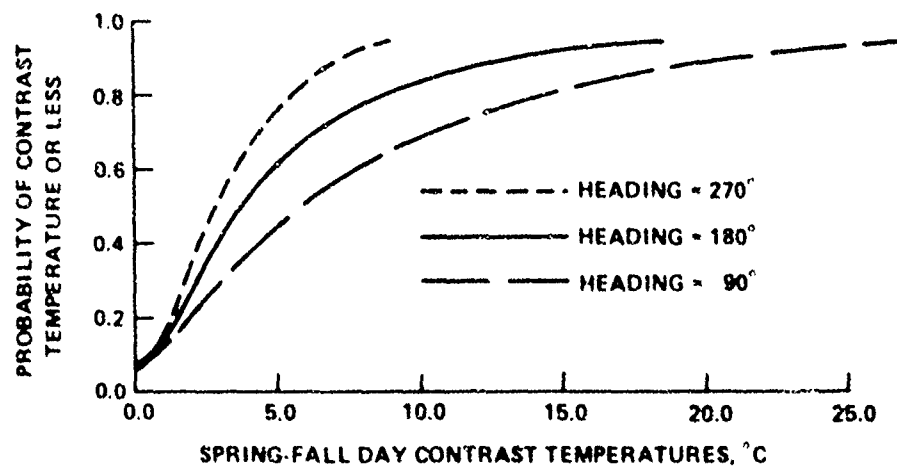
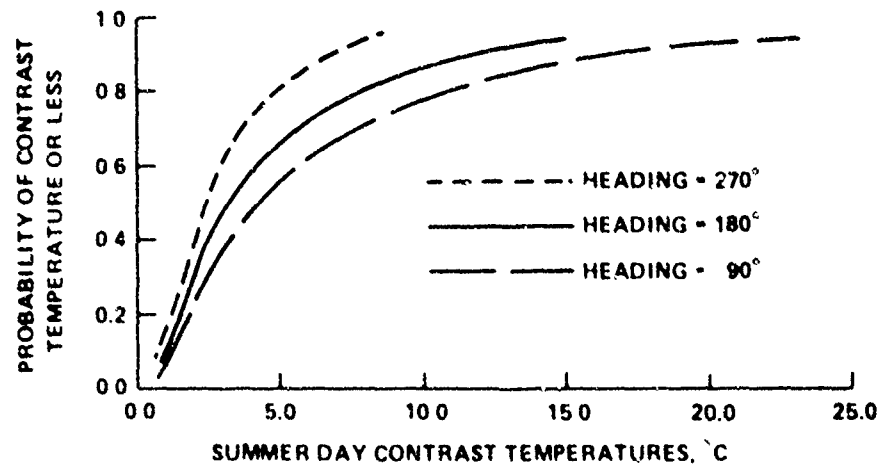
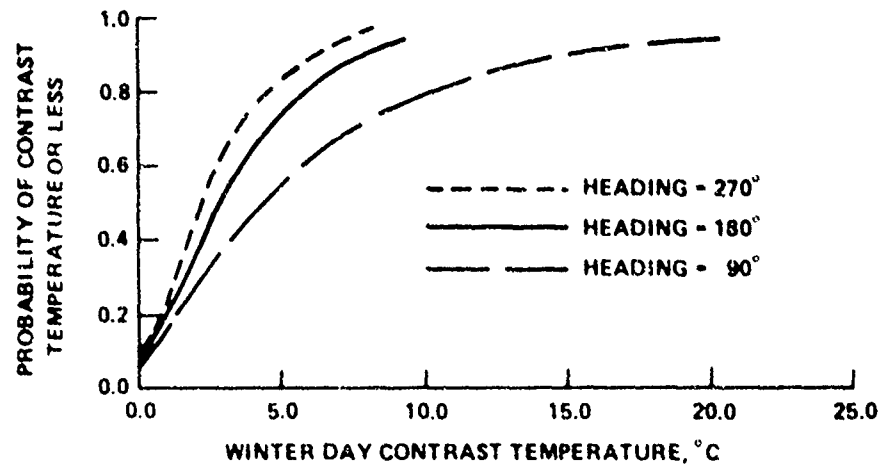


Figure 14. Representative Probabilities of Observing Daytime Contrast Temperatures for Various Ship Headings

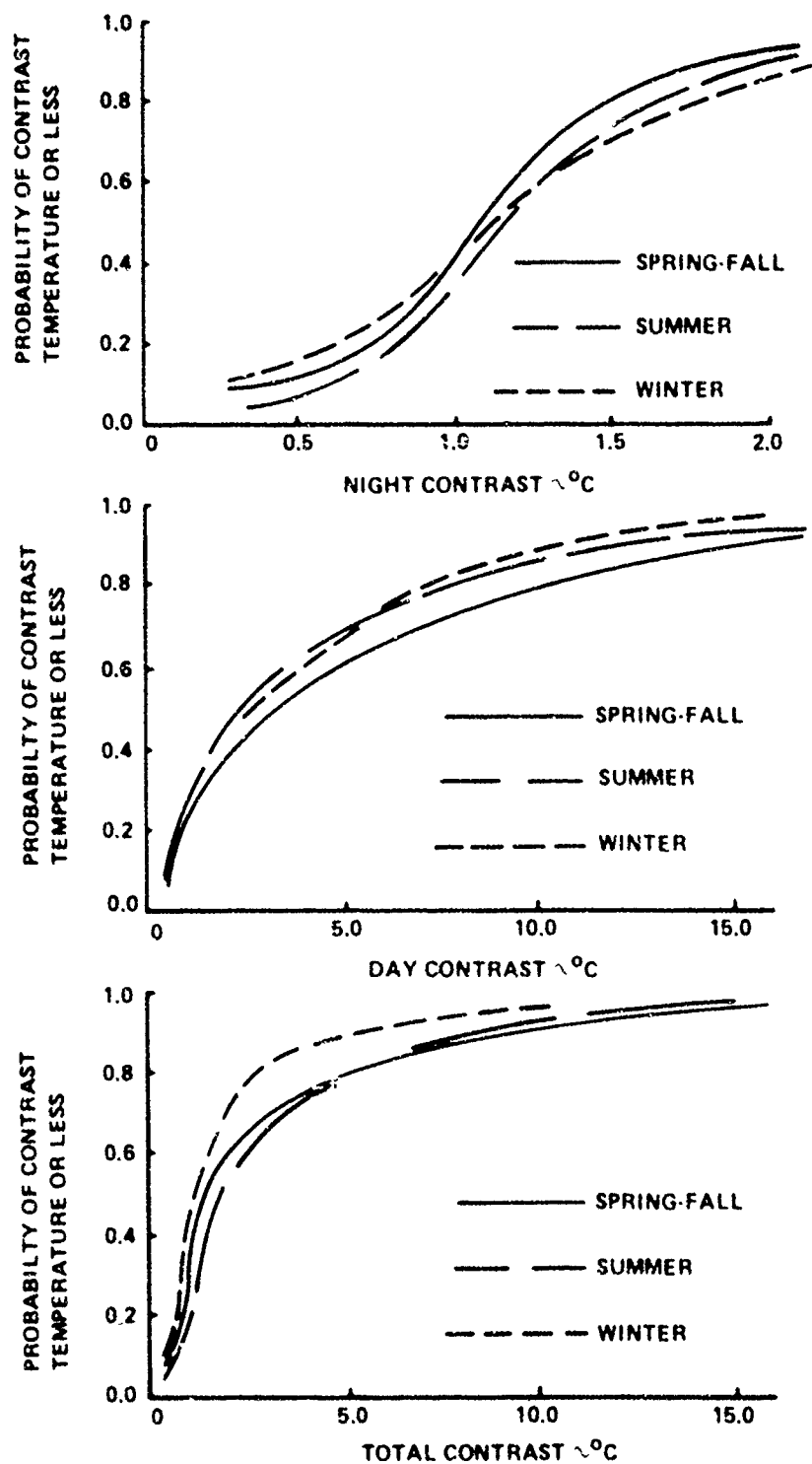


Figure 15. Probability of Observing Ship Contrast Temperatures with Sea Level Air Background

because they are governed by the difference between ambient air and background temperatures. That is, the ship temperatures increase due to internal sources generally contribute only slightly to night contrast temperatures (see Appendix A). However, in the present case of air backgrounds, internal sources are a major contributor to night contrast temperature. Day contrasts are somewhat reduced for the air background but spring-fall values are the highest as they were for a sea surface background (see Figure 10). This also occurs because spring-fall ship temperatures are about the same as those of summer (see Table 3) but background temperatures are lower due to the colder season. The total contrast temperatures of Figure 15 show lower winter values due to the much lower winter ship temperatures. This behavior did not occur with sea surface backgrounds because these have relatively lower background temperatures than the present case (see Figure 9).

Single Element Method

The results of contrast temperature calculations presented in Figures 7-13 and Tables 3-13 were based on the Patrol Frigate Model discussed in Appendix A. This model treats the ship as a single vertical element and applies three correction factors. These corrections account for: (1) variations in ship internal temperatures; (2) variations in thermal capacities of ship construction; and (3) the presence of one or more exhaust stacks. It was shown in Appendix A that the individual correction factors are likely to be small for a ship having a cooled stack. The implication of the correction factors being small is that the features calculated using the Patrol Frigate Model would approximately apply to any similarly constructed ship. To judge the influence of ship model on contrast temperature, the 3 correction factors used in the Single Element Method were summed and statistically analyzed. That is, the probability of occurrence of the sum was computed for each of the seasons in the 1964-71 time period. These were found to be remarkably similar for each season and for each year. The 1966 spring-fall season was chosen as representative and the sum of the correction factors is plotted in Figure 16 for this season.

Figure 16 shows that the total temperature correction factor is rarely above 1.0°C and has a median value of almost 0.5°C . An examination of the ship temperatures given in Table 3 for 8 years of weather data shows that the variation in ship temperature between years is commonly greater than 1.0°C . Furthermore, the temperature additions shown in Figure 15 are small compared to the total temperature rises above ambient ($8-10^{\circ}\text{C}$) shown in Table 3. Hence, it is concluded that the choice of ship model is not critical and that the results predicted herein apply to all similarly constructed ships. However, note that these results use a cooled stack and this conclusion would not hold for a model containing a hot stack.

The work of this report is directed towards finding the target contrast signature that exists at the ship target. This ship target signature is useful in system studies which define system performance from a target contrast temperature such as those performed for the SEAFIRE Program. However, for many other purposes the signal power definition of ship signature is needed. The signal power is defined in equation (1) and this yields the radiant power received which is useful in providing a signal to an infrared system. A consideration of the apparent signal requires that the attenuation of radiance and the emission over air path between the detector and the target be known. Attenuation due to the response of the detector must also be known. Both of these are outside the scope of the present work. However, it is possible to relate the contrast temperature of this work to the radiant contrast which exists at the target. Target radiant contrast is simply the difference between target surface radiance and background radiance integrated

TABLE 4 SKY TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	10.76	10.06	10.24	10.55	10.90	9.48	10.56	10.81	10.15
.90	9.88	8.83	9.13	9.82	9.98	8.18	9.43	9.78	9.03
.80	8.39	7.22	7.62	7.99	7.61	5.97	6.89	8.33	7.81
.70	7.02	5.78	6.06	6.38	5.35	4.03	4.65	6.64	5.53
.60	5.52	3.80	4.58	4.60	3.35	1.90	2.76	5.00	3.71
.50	3.63	2.11	2.80	2.37	1.39	-.07	.81	2.90	1.78
.40	1.11	-.93	.70	.07	-1.54	-3.11	-2.30	.49	-1.00
.30	-4.26	-6.94	-3.19	-4.68	-7.15	-7.73	-8.67	-3.09	-5.88
.20	-12.71	-13.29	-9.91	-11.52	-14.61	-14.39	-15.52	-8.92	-12.22
.10	-22.83	-22.96	-18.26	-20.72	-23.66	-22.71	-28.40	-18.34	-23.33

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	13.44	12.14	11.75	11.80	11.70	12.64	12.89	14.44	13.10
.90	11.88	10.83	10.38	10.42	10.49	11.73	11.55	13.52	11.95
.80	9.46	9.55	8.87	8.67	8.62	9.64	9.68	10.48	9.55
.70	7.69	7.95	7.50	6.97	6.78	8.25	7.62	8.37	7.58
.60	5.92	6.04	5.84	5.44	4.93	6.41	5.77	6.17	5.67
.50	3.37	3.84	3.92	3.76	3.06	4.12	3.26	3.62	3.59
.40	.47	1.53	1.01	1.73	.79	1.09	.43	1.04	1.08
.30	-3.55	-2.75	-2.85	-1.56	-2.85	-3.53	-3.49	-2.52	-2.56
.20	-9.87	-7.85	-8.48	-6.57	-6.82	-9.46	-9.95	-7.69	-8.26
.10	-17.85	-14.41	-15.50	-15.22	-15.03	-18.78	-17.44	-14.58	-16.60

SPRING FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	13.64	13.15	13.40	13.31	13.20	13.00	14.21	14.16	13.61
.90	12.85	12.38	12.66	12.47	11.66	12.47	12.86	13.13	12.40
.80	11.57	11.08	11.51	10.98	10.07	11.26	11.56	11.39	10.82
.70	10.18	9.58	10.17	9.54	8.65	9.61	10.33	10.05	9.49
.60	9.05	8.01	8.89	7.96	7.33	7.88	9.31	8.95	8.32
.50	7.79	6.52	7.58	6.76	5.96	6.46	8.14	7.37	7.05
.40	6.33	4.66	6.15	5.25	4.39	4.64	6.87	5.52	5.63
.30	4.18	1.66	3.87	3.44	1.23	2.07	5.27	2.88	3.25
.20	-1.56	-2.40	-1.29	-.76	-3.02	-3.38	2.43	-.74	-.48
.10	-7.84	-7.72	-7.86	-6.71	-8.07	-8.78	-4.70	-6.09	-6.74

SUMMER (MAY, JUNE, JULY, AUG.)

TABLE 5 DAY CONTRAST TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	16.87	13.52	18.78	17.56	19.23	18.48	18.71	18.51	16.16
.90	12.45	10.41	14.24	13.66	15.31	13.15	14.46	13.01	12.86
.80	8.34	7.69	10.04	9.18	10.76	8.54	10.55	9.09	9.12
.70	6.29	5.89	7.58	7.27	7.84	6.23	8.01	6.86	6.96
.60	4.97	4.92	5.86	5.87	6.10	4.94	5.92	5.38	5.51
.50	3.81	3.69	4.30	4.44	4.75	3.81	4.54	3.94	4.22
.40	2.86	2.89	3.03	3.44	3.47	2.93	3.36	2.90	3.18
.30	2.07	2.10	2.17	2.67	2.26	1.98	2.41	2.19	2.33
.20	1.36	1.33	1.50	1.95	1.41	1.06	1.45	1.32	1.51
.10	.57	.39	.39	1.01	.33	.01	.28	.31	.52

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	26.85	27.95	25.82	24.41	24.83	24.94	22.62	25.79	25.29
.90	20.60	22.32	20.57	17.94	20.03	19.78	17.24	20.44	19.78
.80	14.04	15.91	14.00	12.46	13.43	14.04	11.77	13.97	14.19
.70	10.44	11.53	10.19	9.53	9.51	10.51	9.18	10.30	10.36
.60	7.73	8.57	7.91	7.11	6.87	8.17	7.30	7.55	7.72
.50	5.74	6.21	5.83	5.16	5.12	6.35	5.34	5.60	5.74
.40	3.88	4.42	4.29	3.64	3.80	4.69	3.96	4.03	4.17
.30	2.71	3.07	3.04	2.60	2.72	3.39	2.89	3.00	3.00
.20	1.81	1.99	1.85	1.90	1.81	2.15	1.78	2.12	1.98
.10	.95	.99	.73	.91	.85	1.20	.56	1.13	.88

SPRING FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	19.67	21.90	22.78	20.75	20.86	19.86	17.41	18.91	20.10
.90	14.61	16.84	16.51	15.38	15.86	15.41	13.15	14.62	15.00
.80	9.86	11.04	10.51	10.34	10.72	10.52	8.71	9.52	9.72
.70	7.29	8.18	7.41	7.67	8.16	7.88	6.06	7.14	7.12
.60	5.44	6.30	5.39	5.74	6.35	5.89	4.49	5.47	5.87
.50	4.10	4.82	4.04	4.20	4.71	4.33	3.37	4.03	4.10
.40	3.22	3.66	3.14	3.12	3.58	3.25	2.70	3.15	3.18
.30	2.53	2.74	2.41	2.38	2.67	2.46	2.11	2.42	2.43
.20	1.94	2.05	1.79	1.81	1.96	1.93	1.54	1.72	1.89
.10	1.32	1.33	1.12	1.17	1.20	1.19	.73	.86	1.03

SUMMER (MAY, JUNE, JULY, AUG.)

TABLE 6 10 A.M. CONTRAST TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	11.48	9.66	11.25	13.75	14.83	12.20	14.10	13.30	12.26
.90	9.39	8.33	9.19	11.00	12.43	7.60	13.12	10.10	10.73
.80	7.40	5.77	6.90	7.50	8.30	5.85	8.60	6.45	7.19
.70	5.09	4.59	5.81	5.50	5.49	5.01	6.13	5.66	5.36
.60	4.06	3.70	4.60	4.60	4.68	3.92	4.31	4.71	4.15
.50	3.35	3.17	3.70	3.76	4.16	3.25	3.46	3.64	3.71
.40	3.04	2.25	2.48	3.33	3.38	2.74	2.73	2.72	2.82
.30	2.53	1.27	2.01	2.60	2.36	2.13	2.16	2.16	1.94
.20	1.81	.54	1.07	2.00	1.49	1.22	1.54	1.32	1.27
.10	.81	-.06	1.0	60	87	.36	.49	.45	.36

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	20.85	25.35	20.55	21.81	19.35	21.41	14.90	18.75	20.13
.90	16.70	17.90	18.10	14.90	14.80	18.08	13.20	16.25	16.65
.80	11.60	13.40	12.80	11.13	11.90	14.55	10.95	13.50	12.75
.70	9.03	11.35	10.40	9.52	8.70	10.33	9.22	9.68	10.03
.60	6.98	8.66	8.98	8.20	6.87	8.30	6.43	8.30	7.71
.50	6.05	6.96	7.80	6.38	5.88	6.95	5.29	6.45	6.55
.40	4.24	5.57	6.39	5.28	4.76	5.43	4.34	5.38	5.31
.30	3.39	3.52	5.40	3.38	3.66	4.54	3.37	3.90	4.39
.20	1.64	1.82	3.32	1.92	2.44	2.28	1.92	2.15	2.48
.10	1.03	1.02	1.68	.73	1.26	1.19	.96	1.30	1.21

SPRING FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	18.80	18.45	21.60	16.40	19.76	17.77	14.45	16.50	18.03
.90	14.60	16.53	16.80	14.40	18.09	16.64	10.98	13.00	14.54
.80	11.64	12.20	12.20	10.92	12.80	12.95	8.13	10.00	10.17
.70	9.20	9.97	7.80	8.68	9.77	10.18	6.62	8.50	8.90
.60	6.85	7.93	6.55	6.87	8.63	8.10	5.33	6.83	6.72
.50	5.40	6.67	4.80	5.75	6.00	6.54	4.40	5.90	6.54
.40	4.46	5.45	3.66	4.17	4.36	5.54	3.68	5.08	4.60
.30	3.42	4.22	2.81	2.92	3.34	3.84	2.82	4.07	3.52
.20	2.16	2.74	1.98	2.10	2.44	2.42	1.95	2.35	2.36
.10	1.49	1.37	1.23	1.41	1.36	1.56	1.21	1.20	1.38

SUMMER (MAY, JUNE, JULY, AUG.)

TABLE 7 11 A.M. CONTRAST TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	17.40	11.95	15.40	15.65	17.63	13.94	19.95	17.75	15.95
.90	13.90	8.45	12.96	12.30	13.97	10.90	16.15	12.50	12.30
.80	9.40	6.63	11.12	8.87	10.47	8.75	11.80	9.13	9.22
.70	6.85	5.48	8.93	7.47	8.67	6.44	8.15	8.25	7.21
.60	5.28	4.95	7.62	6.07	7.10	5.58	6.53	6.63	6.29
.50	4.20	4.10	6.58	5.13	5.92	4.55	5.19	4.67	5.34
.40	3.18	3.24	4.52	3.92	4.63	3.67	3.98	3.13	3.83
.30	2.06	2.29	2.46	2.68	3.06	2.45	2.82	2.25	2.56
.20	1.28	1.62	1.87	2.04	1.71	1.27	1.34	1.16	1.60
.10	.52	.22	.48	1.24	.42	.30	.35	.30	.45

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	33.75	27.60	26.30	26.25	28.65	26.65	26.10	25.98	29.87
.90	25.50	24.00	22.20	19.50	22.55	22.73	22.08	23.40	22.50
.80	18.75	21.00	16.08	14.33	18.10	16.80	17.03	16.20	17.67
.70	14.00	17.20	12.80	12.00	15.83	12.30	13.60	12.93	14.60
.60	12.40	14.50	10.57	10.25	11.90	10.24	9.90	10.93	12.20
.50	10.20	11.25	9.25	8.33	9.92	8.65	8.70	9.75	9.79
.40	8.50	8.88	6.90	5.17	7.65	6.13	6.97	8.15	7.03
.30	5.75	5.50	5.10	2.75	5.95	4.48	4.81	5.30	4.35
.20	2.60	2.20	2.28	1.80	3.32	3.08	3.48	3.91	2.86
.10	1.30	1.33	1.42	.80	1.53	1.47	1.24	1.64	1.22

SPRING-FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	23.33	25.95	26.85	20.48	22.65	22.50	17.13	20.38	21.99
.90	17.55	22.92	22.28	17.07	19.70	19.50	15.50	18.47	19.21
.80	12.55	16.27	17.70	13.55	14.63	16.57	11.75	14.73	14.73
.70	10.33	13.93	13.03	11.35	12.04	13.00	9.75	11.06	11.84
.60	8.07	11.95	10.45	9.64	8.70	9.50	7.42	8.40	9.69
.50	6.58	9.17	8.58	7.80	7.10	7.50	6.25	7.44	7.71
.40	5.36	7.40	6.65	6.60	6.28	6.50	5.00	5.83	6.20
.30	4.16	5.60	4.98	4.68	4.96	3.30	3.33	3.57	4.45
.20	2.79	3.46	3.24	2.36	2.64	2.20	2.04	2.55	2.75
.10	1.79	1.85	1.49	1.88	1.66	1.50	.75	1.09	1.32

SUMMER (MAY, JUNE, JULY, AUG.)

TABLE 8 NOON CONTRAST TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	18.00	15.62	19.01	18.90	23.33	18.70	23.03	26.55	21.09
.90	13.60	12.85	16.90	14.80	18.10	13.80	19.35	19.40	16.13
.80	11.00	9.07	13.68	11.40	13.44	10.93	14.20	12.95	11.64
.70	8.20	7.89	11.03	9.13	12.04	8.60	11.62	10.73	9.97
.60	6.38	6.48	8.73	7.43	10.20	7.13	8.63	7.20	8.29
.50	5.25	5.39	7.19	6.30	7.44	5.67	6.75	5.75	6.35
.40	4.60	4.52	5.90	5.22	5.83	4.68	4.86	4.12	5.01
.30	3.20	3.25	3.98	3.32	4.54	3.85	3.95	3.24	3.87
.20	1.90	2.31	2.12	2.48	2.16	2.26	1.84	2.15	2.16
.10	.90	.82	.86	1.62	.79	.36	.33	.57	.98

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	39.75	34.46	33.25	28.95	34.67	33.75	32.17	29.45	34.35
.90	32.83	30.58	27.96	23.85	28.60	25.50	23.76	25.43	28.20
.80	19.70	22.65	22.10	17.52	21.72	21.00	15.20	20.80	18.93
.70	16.78	19.16	17.60	14.57	17.60	17.17	13.20	14.93	16.18
.60	12.70	15.70	12.47	11.32	12.70	13.50	10.68	12.90	13.19
.50	9.13	12.08	10.50	9.25	9.33	11.13	9.17	10.50	10.63
.40	7.22	7.94	8.90	6.70	7.60	9.25	8.05	8.57	7.80
.30	4.56	5.48	5.80	4.06	4.63	7.69	6.05	6.05	5.88
.20	2.38	3.52	3.91	2.42	2.76	4.60	2.56	3.52	3.58
.10	1.46	1.23	1.63	.91	.94	3.20	.94	1.91	2.06

SPRING-FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	27.53	29.43	32.13	28.50	29.15	26.20	20.36	25.45	26.25
.90	20.61	27.35	28.05	23.25	26.40	23.03	18.60	21.68	23.33
.80	17.40	20.31	18.60	18.38	18.94	17.94	15.24	18.76	17.78
.70	12.85	16.07	13.60	13.67	14.47	14.60	11.76	14.90	13.92
.60	10.70	12.54	9.96	11.00	11.48	11.80	8.85	11.43	10.70
.50	8.63	9.92	8.60	9.25	8.80	9.00	6.50	8.88	8.21
.40	6.65	8.53	5.70	7.25	7.43	7.73	4.84	7.23	6.69
.30	3.78	6.36	4.44	5.50	5.80	6.45	3.04	3.92	4.70
.20	2.68	4.01	2.64	3.00	3.32	2.72	2.12	2.88	3.07
.10	1.83	1.75	1.66	1.65	1.84	1.37	.54	1.51	1.26

SUMMER (MAY, JUNE, JULY, AUG.)

TABLE 9 1 P.M. CONTRAST TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	22.29	18.40	24.80	21.68	24.38	24.20	20.48	25.60	22.00
.90	18.30	14.27	19.54	17.27	22.00	19.05	17.69	21.20	18.14
.80	10.80	9.80	14.60	11.70	16.67	13.45	14.20	12.10	13.24
.70	8.29	8.64	11.63	9.43	12.00	10.70	10.60	10.40	10.15
.60	6.80	7.53	9.55	7.83	9.25	8.15	8.37	7.48	8.18
.50	5.66	5.60	7.63	6.81	6.92	6.00	6.33	5.88	6.62
.40	4.16	4.36	5.77	5.73	6.10	4.54	5.22	4.28	4.97
.30	2.82	3.21	3.44	3.34	4.73	3.22	4.22	2.88	3.78
.20	1.84	2.22	2.38	2.68	2.00	2.13	2.49	2.16	2.26
.10	.57	.84	1.34	1.62	.90	.72	.88	.38	1.00

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	38.81	36.00	35.25	31.94	33.03	36.05	34.00	36.06	35.38
.90	32.63	31.17	29.35	25.26	30.50	30.13	22.95	29.78	27.79
.80	23.66	25.58	23.40	19.37	22.35	22.20	17.20	24.17	21.44
.70	18.78	20.66	16.80	15.10	16.95	17.33	12.56	19.10	16.61
.60	15.80	17.32	12.93	12.71	11.87	14.91	10.68	14.80	14.00
.50	10.88	13.80	11.33	11.17	8.92	13.13	9.25	12.25	11.53
.40	8.43	10.85	8.80	7.77	6.20	10.15	8.64	10.20	8.53
.30	5.93	7.13	6.80	3.68	3.53	8.43	6.70	7.48	5.98
.20	2.58	4.64	4.28	2.28	2.12	4.57	4.56	4.12	3.38
.10	1.33	2.46	1.12	1.06	1.27	2.78	1.48	2.22	1.92

SPRING FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	26.10	32.00	32.75	29.31	28.05	28.88	23.66	26.60	28.21
.90	20.34	24.45	28.70	26.03	25.16	25.80	20.61	20.76	24.52
.80	17.07	19.95	20.10	21.72	19.20	19.50	16.13	18.12	18.04
.70	13.13	16.70	14.64	17.55	14.70	14.50	12.58	14.20	16.07
.60	11.31	13.47	11.20	12.27	11.95	12.22	10.20	11.93	11.84
.50	9.00	9.70	8.90	10.30	9.75	9.80	7.58	9.25	8.94
.40	7.45	7.65	7.23	8.62	7.90	7.25	5.58	7.87	7.10
.30	4.84	5.20	5.47	5.11	6.24	3.80	4.34	5.35	5.02
.20	2.74	3.38	4.02	3.86	3.32	2.72	3.08	3.35	3.38
.10	1.97	1.83	2.38	1.86	2.06	2.07	1.38	1.38	1.88

SUMMER (MAY, JUNE, JULY, AUG.)

TABLE 10 2 P.M. CONTRAST TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	21.80	18.50	22.73	22.05	23.00	24.30	19.35	24.87	21.69
.90	16.60	13.75	17.15	18.66	18.75	19.05	16.35	19.35	16.55
.80	11.10	10.50	12.52	13.40	14.50	13.80	10.93	11.27	12.50
.70	7.98	7.75	10.32	9.58	12.00	9.55	9.68	8.93	9.88
.60	6.44	6.30	8.53	7.81	8.50	6.77	7.70	7.56	7.42
.50	5.00	5.31	6.08	6.94	6.75	5.50	6.21	5.75	5.97
.40	3.75	4.00	4.04	4.07	6.00	4.39	5.03	3.96	4.88
.30	2.36	3.10	2.47	3.97	4.07	3.18	3.65	2.73	3.27
.20	1.52	2.30	2.01	2.56	1.80	1.44	2.32	1.95	2.00
.10	.44	1.60	1.27	1.58	.45	.44	.66	.47	1.02

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	30.38	36.06	31.83	39.00	28.30	36.00	31.63	34.50	32.15
.90	27.18	31.42	28.37	28.65	25.73	27.40	24.45	30.00	27.94
.80	19.98	25.44	23.13	21.20	20.70	20.90	18.30	22.50	21.87
.70	16.45	21.37	19.87	14.87	16.53	15.90	13.98	18.43	17.68
.60	13.55	15.80	16.60	13.31	12.80	14.40	10.80	15.40	13.70
.50	11.08	12.75	13.00	10.80	7.83	12.00	9.54	11.67	10.42
.40	7.73	9.70	10.05	8.20	6.10	9.73	7.85	7.25	8.08
.30	4.02	7.48	6.35	5.23	3.48	7.35	6.76	5.88	5.48
.20	2.54	4.44	3.32	2.64	1.96	4.68	4.12	3.40	3.32
.10	1.19	1.87	1.38	1.86	.63	1.96	2.27	1.80	1.45

SPRING-FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	24.45	29.00	31.69	27.30	28.61	27.25	27.20	25.73	28.07
.90	21.80	24.75	26.10	23.85	25.38	22.50	23.10	21.60	23.85
.80	17.47	19.50	19.80	19.92	19.54	16.80	17.45	15.64	17.78
.70	13.70	16.00	14.53	15.80	16.26	14.13	13.60	13.47	14.74
.60	10.47	13.43	10.96	11.34	12.30	11.50	10.60	11.10	11.95
.50	7.17	9.25	8.38	9.88	10.36	9.35	9.13	9.50	8.77
.40	4.81	8.00	5.10	7.30	8.47	7.63	6.60	7.93	6.64
.30	3.47	5.92	4.35	4.44	7.15	4.53	4.38	6.10	5.31
.20	2.31	4.73	3.08	3.16	5.57	2.50	3.04	3.54	3.94
.10	1.82	1.80	2.33	1.87	2.54	1.45	2.12	1.63	2.00

SUMMER (MAY, JUNE, JULY, AUG.)

TABLE 11 3 P.M. CONTRAST TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	17.40	13.66	25.80	17.50	18.85	18.75	21.23	17.25	19.73
.90	13.40	12.15	19.20	14.75	16.28	13.75	14.65	14.00	15.68
.80	9.20	8.45	11.90	10.00	10.73	10.00	11.15	9.42	10.18
.70	6.48	7.15	9.03	7.50	8.05	7.95	9.19	8.60	7.84
.60	5.63	5.20	5.93	6.00	6.23	6.50	7.05	6.33	6.13
.50	5.00	4.15	5.00	4.87	5.04	4.40	4.80	5.64	4.95
.40	3.83	3.05	3.59	3.60	3.96	3.00	4.24	4.20	3.62
.30	1.97	2.17	2.76	2.90	2.38	2.03	3.01	2.70	2.49
.20	1.33	1.52	2.02	2.17	1.46	.87	1.54	1.70	1.52
.10	.36	.85	1.16	1.47	.32	.10	.27	.50	.79

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	29.40	29.25	27.79	32.75	27.93	29.70	31.67	29.00	30.27
.90	23.10	24.75	25.05	27.30	24.10	23.10	22.71	26.50	25.20
.80	17.68	21.30	19.92	17.30	20.07	17.20	18.43	20.50	19.25
.70	14.20	17.63	15.43	13.73	16.20	13.80	13.71	16.00	15.67
.60	12.28	14.25	10.85	11.20	13.70	11.60	12.00	12.25	12.55
.50	9.50	11.50	8.25	9.58	11.17	9.00	9.00	10.17	9.88
.40	6.70	9.00	6.93	7.73	6.15	7.45	7.33	6.88	7.58
.30	4.68	6.18	4.83	5.68	4.14	5.65	5.83	5.00	5.16
.20	2.56	3.00	2.16	2.68	2.08	3.28	3.20	3.50	2.79
.10	.96	1.48	.89	1.74	1.59	1.66	1.20	1.60	1.22

SPRING FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	28.95	26.65	28.65	27.25	26.43	27.08	23.70	25.50	26.33
.90	23.16	24.30	24.15	21.50	23.33	21.83	18.90	21.00	21.60
.80	18.10	18.12	18.20	17.00	18.09	16.05	14.43	15.45	16.32
.70	12.95	14.90	13.30	13.08	13.58	12.73	12.49	12.33	13.70
.60	9.84	11.08	10.69	11.33	11.20	11.07	8.51	11.00	8.94
.50	7.50	8.67	8.83	9.15	9.25	8.79	7.20	8.50	8.23
.40	6.88	6.93	6.60	7.50	7.15	6.26	4.98	7.25	6.25
.30	5.55	5.37	4.88	5.25	6.31	3.97	3.50	3.73	4.81
.20	3.08	2.98	3.08	2.80	4.56	2.58	1.50	3.07	3.13
.10	1.89	1.67	1.19	1.57	2.58	1.50	1.20	1.00	1.90

SUMMER (MAY, JUNE, JULY, AUG.)

TABLE 12 NIGHT CONTRAST TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
95	10.86	10.47	8.90	10.15	10.18	10.13	10.39	10.05	9.88
90	8.83	8.61	7.31	8.12	8.70	7.89	9.18	7.25	8.22
80	6.35	6.19	5.31	5.60	6.27	5.47	6.28	4.96	5.66
70	4.59	4.39	3.93	3.98	4.19	3.90	4.33	3.70	4.15
60	3.32	2.97	3.07	3.14	3.01	2.90	3.00	2.92	3.11
50	2.51	2.25	2.35	2.60	2.37	2.21	2.21	2.37	2.41
40	2.06	1.72	1.80	2.14	1.84	1.62	1.60	1.86	1.87
30	1.58	1.29	1.23	1.71	1.34	1.06	1.02	1.41	1.30
20	1.03	.75	.54	1.21	.79	.45	.44	.93	.83
10	.24	-.15	-.28	.47	-.30	-.62	-.40	.02	.19

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
95	10.04	8.03	9.88	10.06	7.97	10.64	9.80	7.96	9.30
90	8.09	7.09	7.46	7.89	6.88	8.46	7.75	6.80	7.63
80	6.40	5.54	5.86	5.49	5.30	6.08	6.07	5.19	5.86
70	4.97	4.43	4.82	4.06	4.08	4.43	4.51	3.90	4.39
60	3.62	3.48	3.75	3.20	3.16	3.26	3.43	3.19	3.38
50	2.77	2.79	3.02	2.58	2.40	2.55	2.74	2.61	2.71
40	2.29	2.27	2.47	2.13	1.95	2.05	2.16	2.19	2.21
30	1.84	1.77	1.90	1.73	1.49	1.53	1.59	1.68	1.67
20	1.38	1.20	1.29	1.23	.88	1.02	.98	1.25	1.13
10	.66	.39	.60	.18	.02	.36	.17	.55	.34

SPRING-FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
95	7.82	7.31	6.80	6.39	7.32	7.19	6.84	6.07	6.96
90	6.51	6.21	5.97	5.66	6.41	5.85	5.23	4.99	5.75
80	4.71	4.87	4.55	4.33	5.10	4.38	3.63	3.89	4.37
70	3.55	3.73	3.48	3.24	4.06	3.43	2.86	3.06	3.46
60	2.83	2.95	2.77	2.64	3.11	2.78	2.24	2.46	2.68
50	2.25	2.51	2.33	2.21	2.47	2.31	1.89	2.12	2.20
40	1.87	2.12	1.95	1.87	2.04	2.00	1.64	1.77	1.88
30	1.54	1.76	1.60	1.56	1.76	1.63	1.31	1.40	1.54
20	1.19	1.31	1.25	1.20	1.37	1.31	.91	1.06	1.14
10	.70	.78	.62	.63	.65	.74	.31	.60	.55

SUMMER (MAY, JUNE, JULY, AUG.)

TABLE 13 TOTAL CONTRAST TEMPERATURE FOR SHIP J(1964-71)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	12.09	11.30	12.41	12.35	13.11	12.09	12.87	12.33	12.21
.90	9.76	9.28	9.43	9.67	10.46	9.65	10.49	9.41	9.89
.80	7.15	6.65	6.76	6.95	7.49	6.40	7.88	6.38	6.94
.70	5.29	5.14	5.01	5.14	5.66	4.75	5.53	4.61	5.14
.60	3.88	3.64	3.69	3.78	3.93	3.49	4.03	3.42	3.76
.50	2.83	2.67	2.77	3.00	2.31	2.68	2.84	2.72	2.84
.40	2.26	2.04	2.12	2.44	2.16	1.92	1.99	2.14	2.18
.30	1.71	1.48	1.52	1.95	1.55	1.27	1.38	1.60	1.61
.20	1.15	.91	.82	1.35	.92	.60	.63	1.02	.98
.10	.38	.02	-.16	.62	-.00	-.39	-.24	.10	.00

WINTER (JAN., FEB., NOV., DEC.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	20.38	22.22	20.42	17.73	19.84	19.63	16.88	20.33	19.56
.90	13.84	15.72	13.81	13.00	13.26	13.94	11.93	13.91	13.83
.80	9.22	9.28	9.02	8.61	7.94	9.71	8.47	8.48	8.61
.70	6.82	6.67	6.60	6.16	5.90	7.20	6.45	6.24	6.56
.60	5.18	5.08	5.17	4.45	4.49	5.34	4.86	4.51	4.90
.50	3.69	3.82	3.99	3.32	3.38	3.86	3.62	3.51	3.66
.40	2.72	2.88	3.02	2.57	2.52	2.79	2.76	2.75	2.77
.30	2.12	2.15	2.26	2.01	1.90	2.07	1.99	2.16	2.06
.20	1.53	1.50	1.52	1.51	1.26	1.42	1.24	1.51	1.39
.10	.79	.74	.63	.48	.33	.70	.35	.78	.56

SPRING-FALL (MAR., APR., SEPT., OCT.)

PROB	1964	1965	1966	1967	1968	1969	1970	1971	REP
.95	16.61	18.55	18.89	17.53	18.19	16.85	14.96	15.83	16.93
.90	11.44	13.23	12.47	11.94	12.47	12.30	10.56	11.23	11.90
.80	7.13	8.10	7.37	7.45	8.06	7.84	6.56	7.15	7.32
.70	5.57	6.07	6.43	5.54	6.18	5.71	4.58	5.18	5.38
.60	4.18	4.72	4.10	4.12	4.75	4.23	3.40	3.88	4.08
.50	3.27	3.59	3.19	3.08	3.63	3.25	2.72	3.06	3.18
.40	2.58	2.78	2.50	2.45	2.75	2.53	2.12	2.39	2.45
.30	2.03	2.22	1.99	1.95	2.12	2.07	1.71	1.89	1.97
.20	1.56	1.73	1.51	1.51	1.69	1.56	1.24	1.37	1.49
.10	1.00	1.06	.95	.92	.98	1.02	.53	.72	.80

SUMMER (MAY, JUNE, JULY, AUG.)

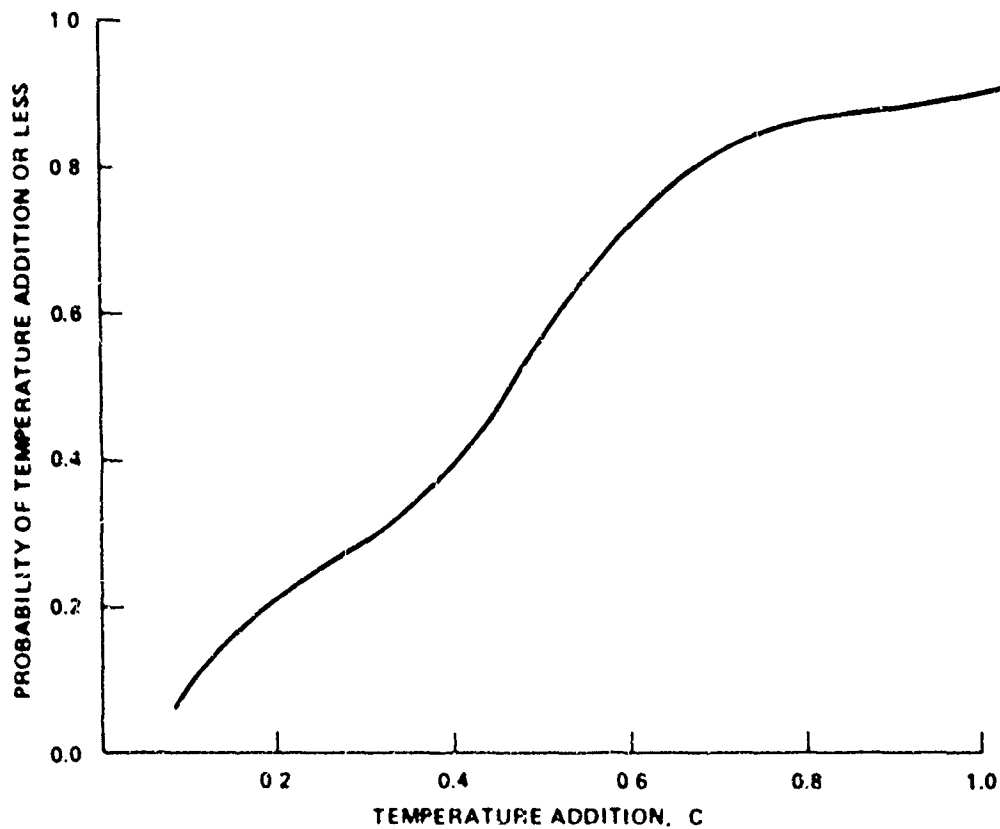


Figure 16. Probability of Observing Temperature Correction Factor of the Single Element Method

over the wavelength region of interest (8-12 μ m). The ship and background temperatures were designed to approximately reproduce the target surface radiance and the background radiance respectively when used in the blackbody spectral radiance (Planck's) equation [equation (3)]. Thus, these temperatures are used to compute spectral radiances and these are integrated numerically over the 8-12 μ m region to find the ship contrast radiance. Contrast temperatures are composed of independent ship and background temperature components. While the radiance from each of these two sources is uniquely related to the real or effective temperature, there is not a unique radiance associated with their temperature difference. This is illustrated in Figure 17 which shows a range of radiant contrasts corresponding to background temperatures of 5°C and 15°C.

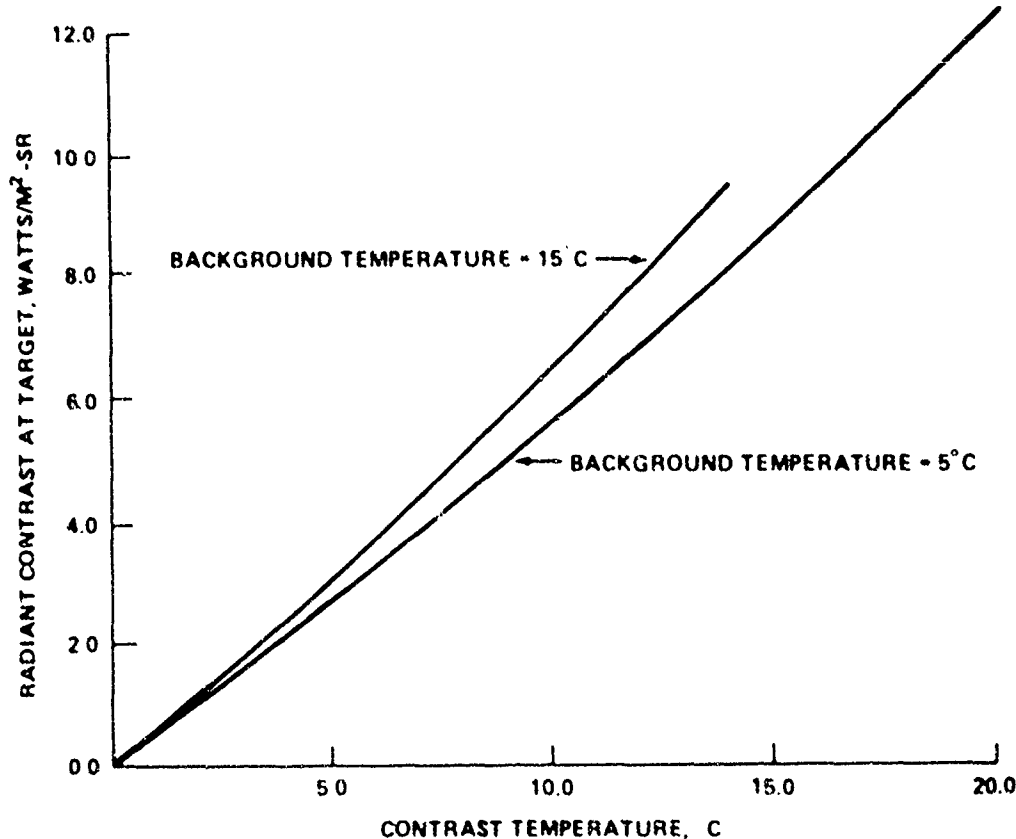


Figure 17. Relationship between contrast temperature and radiant contrast ship signatures

These curves show that the range of radiance contrasts corresponding to a contrast temperature increases with contrast temperature. However, this range is not large for in the background and contrast temperatures encountered in the present work, i.e., median contrast temperatures of 5°C or less. In fact, an average value chosen from Figure 17 will adequately relate any of the previously given contrast temperatures to the target radiant contrast. Recommended average values will be given in the next section of this report.

VII. CONCLUSION

This report has presented the results of a study whose goal was to provide ship signatures in a form useful to SEAFIRE system performance studies. Since the SEAFIRE thermal imaging sensor operates in the 8-12.μm region, all work of the present study was directed towards that waveband. The results presented and the conclusions drawn will not hold for the 3-5.μm or any other waveband. However, the methods developed could be extended to the 3-5.μm waveband by considering the effect of the ship exhaust plume and redefining the background temperatures. SEAFIRE system studies required a statistical distribution of target/background temperatures which include weather effects typically encountered at sea. It was found that existing methods of determining ship signatures are long and involved computationally. Hence, a relatively large amount of expensive computer time would be required to present an analysis of the effect of weather on ship signatures. Therefore, a simpler method of computing contrast temperatures was devised so that a large number of signatures using weather data could be generated. It was shown that this method, named the Single Element Method, provides a good approximation to the average ship temperature. This method will accurately include the effect of a hot stack on average ship temperature. However, the average ship temperature is not meaningful in cases where the small stack surface area contributes half or more of the total temperature. In these cases, the stack will probably be sensed at a much greater distance than the remaining ship. Furthermore, the most obvious countermeasure for a ship signature is to cool the stack hence it may be assumed that future warships will have some form of cooled stack. The average ship temperatures and resulting contrast temperatures calculated were for a ship model having a cooled stack. For this case, it was shown that differences in ship construction or internal temperature distribution do not significantly effect its average temperature hence the results given will have general application. Improvements in the Single Element Method could still be made. The most noteworthy improvement being the obtaining of a model atmosphere that varies continually with day of the year. Also, any advance in methods of computing ship signatures could be incorporated into this method as they become available.

It is difficult to summarize the ship contrast temperatures given in this report because they are greatly influenced by several variables. First, solar heating influences ship temperatures hence the target ships heading and its location on the earth are important. Secondly, weather conditions (i.e., rain, wind, air temperature and cloud cover) largely govern daily signatures and these can also depend on location or season of the year. Finally, the relative positioning between the target and the sensor could be important, especially in determining backgrounds. A summary of day, night and total ship contrast temperatures provided in the previous section is given in Table 14 for a sea surface background. This summary consists of the probability of observing contrast temperature ranges or lower values for year-round conditions when the effect of season and ship's heading are considered. Here, the heading of 270° (due west) on

a starboard element is excluded from daytime contrast temperature because it leads to contrast temperatures very similar to nighttime values.

Table 14. Range of Computed Ship Contrast Temperatures

<u>Probability</u>	<u>Daytime Range</u>	<u>Nighttime Range</u>	<u>Total Time Range</u>
0.90	8-20°C	6-8°C	8-13°C
0.50	3-5°C	2-2.5°C	2.5-3.5°C
0.10	0.5-1°C	0-0.5°C	0-1°C

Table 14 can be used to provide quick estimates of ship target contrast temperatures which can also be converted to contrast radiance by use of Figure 16. However, the limitations imposed by using the Ship J weather data should be remembered. First, Ship J was at a midlatitude location (51°N) and these signatures are expected to vary with latitude. Second, it was noticed after these signatures were computed that the location of Ship J contains an extraordinary amount of cloudy weather. Cloud conditions act both to lower ship temperatures and increase background temperatures thereby leading to low values of contrast temperatures. Hence the contrast temperatures listed in Table 14 are conservative estimates for the midlatitude location. Finally, these estimates are for viewing a ship target from another ship and do not hold for viewing the ship from an aircraft or elevated ground station.

SYMBOLS

a	solar absorptance
A	area fraction of ship surface area with respect to internal temperature
AF	angle factor for solar reflection off of a ship
AS	ship surface area, m
Az	solar azimuth angle, degrees from north
b	solar hour angle, degrees
B	area fraction of ship surface area with respect to heat capacity
c	latitude, degrees
C	area fraction of ship surface area with respect to ship stack
d	solar declension, degrees
D	grouping of variables for internal temperature effects [see equation (25)]
E	second grouping of variables for internal temperature effects [see equation (26)]
f	fraction of clear sky
F	grouping of variables for thermal capacity effects [see equation (21)]
G	second grouping of variables for thermal capacity effects [see equation (22)]
ha	convective coefficient for air flowing over a vertical surface, watts/m ² - °C
hi	internal heat transfer coefficient, watts/m ² - °C
hk	convective coefficient for stack gases, watts/m ² - °C
hr	convective coefficient for rain on a vertical surface, watts/m ² - °C
H	altitude above sea level
HA	dimensionless parameter for air cooling
HI	dimensionless parameter for internal heating
HK	dimensionless parameter for stack gas heating
HR	dimensionless parameter for rain cooling
l	length of air path from target to sky background
M	target ship heading, degrees clockwise from north

Nb	sea surface or background radiance, watts/m ² - sr - μ m
Nc	cloud radiance, watts/m ² - sr - μ m
Ng	apparent background radiance, watts/m ² - sr - μ m
Ns	sky radiance, watts/m ² - sr - μ m
Nt	target surface radiance, watts/m ² - sr - μ m
P	radiative signal power, watts/m ²
Qd	direct solar energy incident on a vertical element, watts/m ²
Qf	diffuse solar energy, watts/m ²
Qi	indirect or diffuse solar energy on a vertical element, watts/m ²
Qo	direct solar energy, watts/m ²
Qs	total solar energy absorbed on a vertical element, watts/m ²
R	spectral blackbody radiance, watts/m ² - sr - μ m
Rs	spectral radiance of sun, watts/m ² - sr - μ m
S	atmospheric radiance emission, watts/m ² - sr - μ m
Sa	atmospheric emission of a clear sky, watts/m ² - sr - μ m
Sc	atmospheric emission of path from target to clouds, watts/m ² - sr - μ m
T	temperature
Tb	basic element or average ship temperature, °C
TC	ship target contrast temperature [see equation (39)]
TC1	internal temperature correction factor, °C
TC2	thermal capacity temperature correction factor, °C
TC3	stack presence temperature correction factor, °C
TH	ship target contrast temperature [see equation (39)], °C
TK	temperature of exhaust gases inside ship stack, °C
Tn	internal temperature of ship compartments, °C
To	sea level temperature or initial ship temperature, °C
TS	effective average ship temperature [see equation (30)]
Tw	sea surface water temperature, °C
Ty	effective sky temperature, °C
Ua	atmospheric transmission
Uas	loss in direct solar energy due to aerosol scattering
Ums	loss in direct solar energy due to molecular scattering
Ut	solar energy transmission
v	relative wind speed between air and ship velocities, m/sec
V	ratio of time step to thermal capacity [see equation (30)]

W	thermal capacity of ship surface sections, watt-hrs/m ² - °C
Z	solar zenith angle
Zp	target-detector zenith angle [see Figure (1)]
Ω	solid angle of target area in detector field-of-view, sr
r	normalized detector response
ε	emissivity in 8-12.μm waveband
Δt	time step in numerically computing ship temperatures, hours
λ	wavelength, μm
θ	elevation angle of sea surface facets, degrees
φ	reflection angle of sea surface facets, degrees

SUBSCRIPTS

a	air
c	clouds
m	internal temperature divisions of ship
min	minimum
p	thermal capacity divisions of ship
q	stacks of ship
s	ship
w	sea surface

APPENDIX A

APPLICATION OF SINGLE ELEMENT METHOD

This appendix will describe how the Single Element Method is applied to a given ship, the Patrol Frigate, to evaluate the correction factors referred to in equations (27), (33) and (36). The basic element of this method is simply a vertical rectangle of unit area which has the lowest internal temperature and lowest thermal capacity of all ship sections considered. This element is basically the same for all similarly-constructed ships. The magnitude of the correction factors vary with differences in ship construction and operation and cause differences in average temperatures between ships. However, it will be shown that these correction factors are small in comparison with the basic element temperatures as computed by the Single Element Method for the Patrol Frigate are a good approximation for all similar ships. Here, similar ships are those having aluminum superstructures and steel hulls of equivalent thickness and relatively small cooled stacks as those found on the Patrol Frigate Model.

A portion of the Patrol Frigate Model indicating the internal temperatures, heat transfer coefficients and thermal capacities is given in Table 1. Here, a broadside view of the starboard side of the ship is divided into 33 sections and these variables are specified along with the surface area for each section. Table A-1 shows that the internal heat transfer coefficient is $0.625 \text{ watts/m}^2 \cdot ^\circ\text{C}$ over most of the ship hence this value is used in the single element method. The starboard view is arbitrarily chosen as any view can be obtained from the 3-dimensional Patrol Frigate Model. In specifying the starboard view in Table 1, the 3-dimensionality of the ship is neglected. That is, all of the sections listed are assumed to be vertical and the slight tilt of some sections is not considered. Correction factors are derived from Table 1 by considering the ship first in terms of its internal temperatures and subsequently in terms of its thermal capacity.

The internal temperatures are modeled by first grouping the sections listed into 3 temperature regions. These are: (1) $80-95^\circ\text{F}$; (2) $100-110^\circ\text{F}$; and (3) $120-140^\circ\text{F}$. The area fractions for each of these regions are found by summing their surface areas and dividing by the total surface area of the starboard view (1130 m). The following area fractions result and are applied at the listed intermediate temperatures.

Temperature	85°F	105°F	130°F
Area Fraction	0.441	0.453	0.016

The temperature correction factor for internal temperature differences can be derived from the above table and equation (27). Let, $A_2 = .453$, $A_1 = .106$, $T_{n_2} - T_{n_1} = 20^\circ\text{F}$ (11.1°C) and $T_{n_1} - T_{n_0} = 45^\circ\text{F}$ (25°C). Equation (27) reduces to

SECTION IDENTIFICATION	AS	Ti	hi	W
Peak Tank	35.1	85	2.660	10.4
Boson Storeroom	46.4	105	0.625	10.4
Hull Storeroom	93.5	105	0.625	10.4
Passage	21.0	105	0.625	8.65
Passage	32.4	105	0.625	10.4
Crew Living Complex	68.3	80	0.625	10.4
Passage	33.4	95	0.625	13.9
Laundry Room	31.4	80	0.625	8.65
Passage	26.8	95	0.625	17.3
Dry Provisions Storeroom	15.6	85	0.625	8.65
Service of	4.8	105	0.625	8.65
Passage	31.6	110	0.625	17.3
Auxiliary Machinery Room 2	21.1	120	0.625	8.65
Passage	35.5	130	0.625	13.9
Engine Room	28.2	140	0.625	10.4
EOS Room	30.2	80	0.625	10.4
Auxiliary Machinery Room 3	21.6	120	0.625	8.65
Central Office Complex	33.6	80	0.625	8.65
Supply Storeroom	28.2	105	0.625	8.65
Gas Cylinders ETC. Room	35.0	105	0.625	8.65
Steering Gear Room	30.8	85	0.625	8.65
Auxiliary Machinery Room 1	13.6	120	0.625	8.65
Helicopter Hanger	176.0	105	0.625	4.09
Ammunition Magazine	139.2	80	0.625	4.09
WR Mess Room	14.1	80	0.625	4.09
WR Pantry	14.4	90	0.625	4.09
Plenum	23.8	105	0.625	4.09
Passage	5.0	90	0.625	4.09
Helicopter Shop	3.4	100	0.625	4.09
Ammunition Magazine	14.2	85	0.625	4.09
Fan Room	10.8	105	0.625	4.09
OTOM	5.8	95	0.625	4.09
Main Stack	12.6	825	26.0	11.0

AS = Surface Area in M²hi = Internal Heat Transfer Coefficient
in watts/M²-°C

Ti = Internal Temperature in F

W = Thermal Capacity in Watt-Hrs/M²-°CTABLE A-1 Internal Temperature and Thermal Capacity Model for
Starboard Side of Patrol Frigate

$$T = T_b + 6.16 \cdot E \quad (A-1)$$

Equation (A-1) shows that the internal temperature corrections depend on E which is composed of the thermal capacity of the basic elements W, the weather coefficients, h_a , h_r , and the time step, Δt [see equations (18)-(20)]. A maximum value of this correction can be calculated for the Patrol Frigate Model. The maximum E results for minimum convective cooling coefficients. Here, $h_r = 0$ (no rain) and $h_a = 6.0$ watts/m² - °C (free convection, no relative wind). The thermal capacity of the basic element is 4.09 watt-hr/m² - °C and the time step is 1.0 hour (time step has only a small influence on this calculation). With these values, the following value for maximum temperature correction factor results.

$$TC1 = 0.36^\circ C \quad (A-2)$$

It was shown in Table 3 that ship temperatures up to 20°C above ambient were calculated from the weather data. Since the higher ship temperatures correspond to the minimum cooling rates which produced the maximum value of temperature correction, this factor will be small compared to the difference between ship and ambient temperature during daylight hours. At night, the internal temperatures may contribute significantly to ship temperature but will not dominate the resulting contrast temperatures. For example, median nighttime contrast temperatures for the Weather Ship J data were found to be about 2.5°C (see Table 14). Thus, the contribution of internal temperature differences to contrast is likely to be small compared to the solar heating effect in daytime or the ship to background temperature differences at night. Also, the rather large internal temperatures given for some sections of the Patrol Frigate Model will not have a significant influence on the results.

The Thermal Capacity Model was derived by first grouping the ship sections listed in Table 1 into common thermal capacities. It was decided that only the three lowest thermal capacities would be considered and that those thermal capacities above 10.4 watt-hr/m² - °C would be neglected because their associated surface area is small. The following area fractions were found for the three lower capacities.

Thermal Capacity (watt-hr/m ² - °C)	4.09	8.65	10.4
Area Fraction	0.408	0.257	0.335

Here the basic element thermal capacity, 4.09 watt-hr/m² - °C, corresponds to the 1/4-inch thick aluminum plating found on the superstructure while the higher values correspond to the steel hulls. The temperature correction factor for thermal capacity differences can be derived from the above table and equation (33). Let, $B_1 = .256$, $B_2 = .335$ and $V_1 = .244$, $V_2 = .116$ and $V_3 = .096$ for a time step, Δt , of one hour. Equation (33) can be written as

$$T = T_b - .0825 \frac{(F - G \cdot T_o)}{1 + .356 + .0256^2} \quad (A-3)$$

where the slight difference in denominator between the two terms of the temperature correction factor has been neglected. The temperature correction factor in Equation (A-3) is a complex combination of the solar heating, internal heating and convective cooling rates which define the factors F and G [see equations (31) and

(32)j. An estimate of this correction is made by assuming that the initial ship temperature is 20°C for the minimum cooling conditions previously defined. The following thermal capacity correction is found for an average absorbed solar heating rate of 75 watts/m^2 and an average air temperature of 10°C .

$$\text{TC2} = -0.42^{\circ}\text{C} \quad (\text{A-4})$$

Thus, the contribution of thermal capacity differences to the average ship temperature calculated by the Single Element Method is also likely to be small compared to the other contributions.

The stack correction factor for the single stack found on the Patrol Frigate is estimated using Equation (37) and noting that the stack area fraction is .0106 from the data in Table 1. The following estimate of maximum stack correction results by using the minimum cooling rates.

$$\text{TC3} = 2.88^{\circ}\text{C} \quad (\text{A-5})$$

If the previously recommended average cooling condition, $\text{HC} + \text{HR} = 5.0$, is used, the stack correction factor drops to 1.50°C . Table 14 indicates that median contrast temperatures for the Weather Ship J data are about 2.5°C at night and 5°C during the day. Thus, the stack correction factor is likely to be a significant portion of the overall ship temperatures for hot stacks. However, the stack correction factor is much reduced for ships having cooled stack or stack gases. For example, if it is assumed that the stack gases are cooled to 150°F (66°C), the corresponding maximum stack correction is $.363^{\circ}\text{C}$ and the average correction is only $.189^{\circ}\text{C}$. A stack gas temperature of 150°F is artificially low to account for stack casing cooling which cannot be considered in the present models.

The work of this appendix shows that the temperature correction factors for ships with cooled stacks are relatively small compared to the expected overall ship temperatures. Hence, ship temperatures calculated by the Single Element Method using the Patrol Frigate Model are valid for all similarly constructed ships. The work on stack correction factors shows that hot stacks contribute significantly to the average ship temperature hence their effect should be included in Single Element Method calculations on a per ship basis. However, hot stacks may be the dominant feature in some ship signatures hence an average ship temperature may not be meaningful in these cases.

APPENDIX B

COMPUTER PROGRAM FOR CALCULATION OF SHIP CONTRAST TEMPERATURES

A computer program using the methods of this report was written to calculate ship contrast temperature and the component temperatures making up its definition. Component temperatures are the sky, background and ship temperatures and these are calculated and presented as an aid in understanding the probabilities of occurrence of contrast temperatures. Contrast temperatures are calculated from data supplied hourly for day operation, night operation, total time operation and for the hours between 10 a.m. and 3 p.m. These calculations are gathered, statistically analyzed, and printed in a form useful in systems studies. The definition of the probability of occurrence of contrast temperature and the rationale for this definition was given in Section V of this report.

The ship contrast temperature program, named ASIRCT for Approximate Ship Infrared Contrast Temperature, will be described. This description will consist of a flow diagram, a listing and a written description of the operation of the main routine and subroutines of this program. These are given to show how weather data is used and how calculations are performed but not to provide a user's manual for the program. However, the program and instructions for its set-up and use may be obtained from the Naval Surface Weapons Center. The ASIRCT program was written specifically for the Patrol Frigate Model and for the 8-12 μ m waveband. However, this program can be modified to include other ships or wavebands using the basic format of this program.

The ASIRCT Program consists of a main routine and eight subroutines. A flow diagram for this program is given in Figure (B-1) and the individual routines are listed in Figures (B-2)-(B-10). The program requires three punched cards and a magnetic tape containing the weather ship data. The three cards are initially read in to provide program controls, the Single Element Method thermal model, and the ship target conditions. These are the only input data cards required as shown by the flow diagram in Figure (B-1). The Program Control Card provides options over printing or plotting the temperatures generated and the option of calculating statistical results either monthly or for a season of several months. Three standard seasons were chosen for data analysis. These are: (1) the winter season, November, December, January and February; (2) the spring-fall season, March, April, September and October; and (3) the summer season, May, June, July and August. The Single Element Method Card provides the thermal capacity and internal temperature model for a ship of three thermal capacities and three internal temperatures. Lastly, the Target Conditions Card provides the speed and heading of the target ship, its emissivity in the waveband of interest (8-12 μ m here), its solar absorbance and its stack model.

Program ASIRCT first calls subroutine SKRAD which provides the clear and cloudy sky radiances in tabular form for future use. This subroutine, which is

listed in Figure (B-3), contains both the Midlatitude Winter and Midlatitude Summer Atmosphere Models. Midlatitude Winter is arbitrarily used for the months November-March and Midlatitude Summer for the remaining months. The program now enters a large loop which begins by reading the weather data tape as seen in Figure (B-1). The weather tape provides a myriad of information, only a portion of which is used by the program. Useful information includes day, month and location of the weather ship, hour of day, sea level conditions of temperature, dewpoint, visibility and wind velocity and cloud height and conditions. This information was recorded hourly by Weather Ship J hence it will be used to calculate contrast temperatures hourly. The large loop of Program ASIRCT takes an hourly reading of weather data and calculates the contrast and component temperatures for this sample. It then returns to the beginning of the loop and repeats the process for another hourly reading of data. The temperatures calculated are all saved for the statistical analysis which is performed after completing the loop. A description of large loop operation follows.

After reading the weather data, the program next determines if subroutine SKRAD should be called to provide new sky radiances. SKRAD is called only if the date indicates a change in season from midlatitude winter to summer or vice-versa has occurred. This happens on either April 1 or November 1 for the two possible seasons. The program next calls subroutine CLDTR. This subroutine, which is listed in Figure (B-4), provides the cloud conditions, cloud transmission and rain convective coefficients. Cloud conditions are taken from the weather data and categorized into 7 general conditions for later printing for informational purposes. From cloud type and altitude, the transmission of solar energy is determined using information from Reference B-1 as a guide. Rain conditions were subdivided into light, medium and heavy drizzle and light, medium and heavy rain for use with the rain convective coefficients derived in Section II of this report. Control of the program returns to the main routine which proceeds to call subroutine NEWDAY if the weather data indicate the start of a new day. This subroutine, which is listed in Figure (B-5) finds the hour of sunrise and sunset of the new day. The main routine then calls subroutine SOLAR which is listed in Figure (B-6). This subroutine calculates the convective cooling coefficient due to relative ship motion which is given by Equation (16). Then, if the sun is present for the hour under consideration, the indirect, direct, and absorbed solar energies which are given by equations (13)-(15) are computed. Control of the program returns to the large loop where the ship temperature including correction factors are calculated by the Single Element Method given in Section V of this report. Subroutine TRSKY, which is listed in Figure (B-7), is then called. This subroutine first determines the sky radiance using Table 2 and the wind speed, cloud height and cloud cover supplied by the weather data. Subroutine TRSKY includes the variation of sky radiance with relative humidity although this has only a small influence as previously explained. This was included before it was realized its effect was small and is retained in case future analyses depending on relative humidity are developed. The sky radiance found is related to sky temperature using the blackbody relationship given in Figure 5. Using the just found value of sky radiance, the background and contrast temperatures are computed. These are stored for future use in determining probabilities of occurrence by statistical analysis. Next, subroutine CONHR is

is called if the hour of day is between 10 a.m. and 3 p.m. This subroutine, which is listed in Figure (B-8), stores contrast temperatures for the above hours when they are likely to be at their maximum values. Control of the program returns to the main routine where the large loop ends by determining if the hourly data calculated is to be printed. If printing is desired, many quantities in addition to the contrast and component temperatures are printed for information. These include the indirect, direct and absorbed solar energy, the wind speed and direction, the cooling coefficient, sky radiance, rain coefficient, air and sea temperature and the generalized cloud condition. The program now either returns to the beginning of the loop for more weather data or leaves the loop to statistically analyze the temperatures stored.

Data are statistically analyzed after 1 month or a specified number of months of contrast temperatures, computed hourly, have been stored. This is done by calling subroutine ANAL whose main purpose is to call subroutine SORT which actually performs the statistical calculations, subroutine ANAL, which is listed in Figure (B-9) calls SORT once for every contrast temperature or component temperature calculated in the main routine. These are, the component temperatures for ship, sky and background and the contrast temperatures for daytime, nighttime, total time and the six hours between 10 a.m. and 3 p.m. SORT is also called to find probability of occurrence for the sum of the three correction factors, TC1, TC2 and TC3. After these calls to SORT, subroutine ANAL prints a summary table of the probability of occurrences found in SORT. These tables will be reproduced and given in Section V of this report. Subroutine SORT, which is listed in Figure (B-10), calculates the probability of occurrence of temperatures which are given as a list of standard temperatures. These probabilities are printed and as an option may be plotted using a Gould electrostatic plotter, for example. After the summary table is printed, control of the program returns to the main routine where it either ends or returns to the beginning of the main loop to read more weather data.

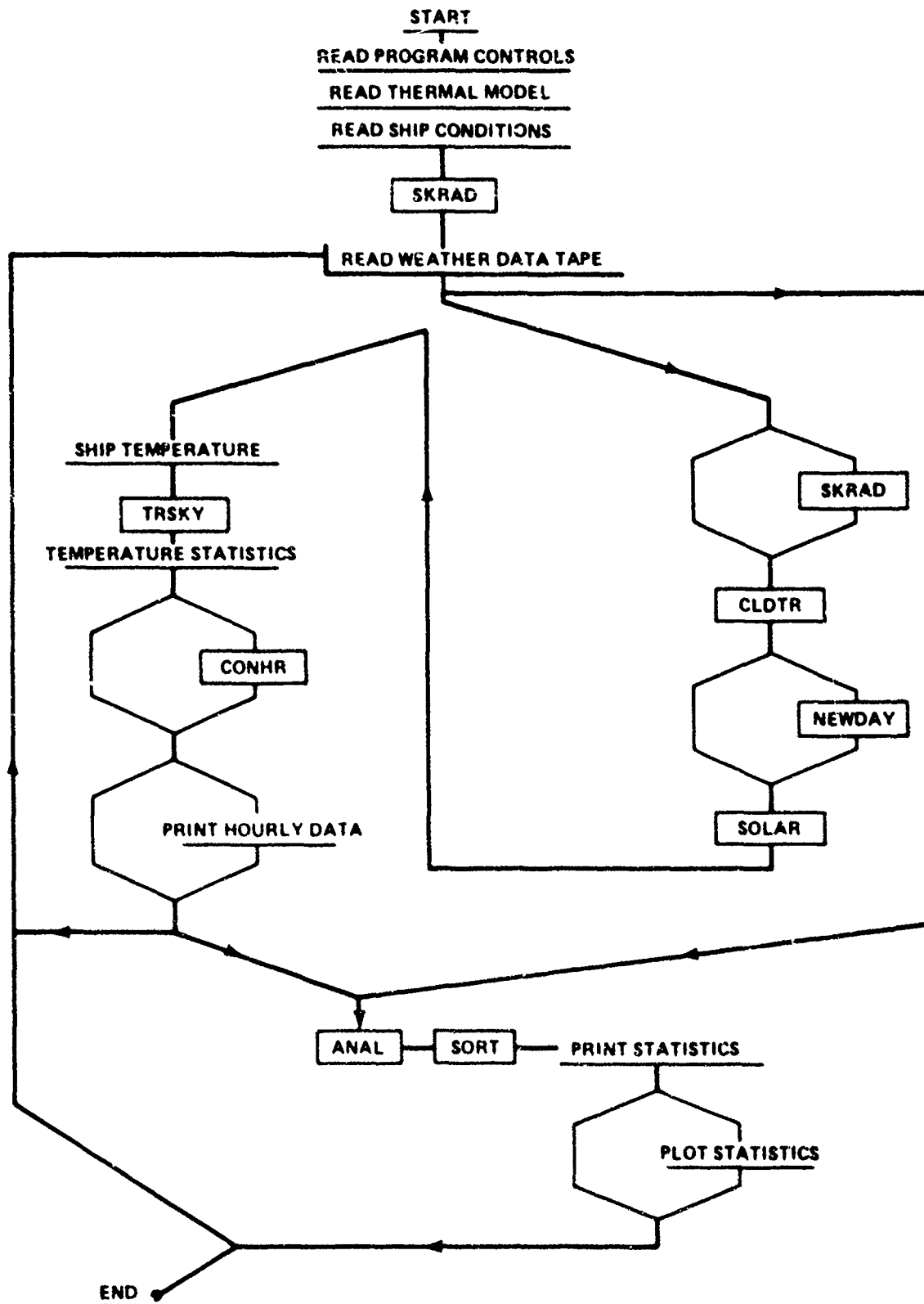


FIGURE B-1 FLOW DIAGRAM OF ASIRCT PROGRAM

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PROGRAM ASIRCT(INPUT,TAPE1,OUTPUT)
COMMON/DAYH/IMONTH, IDAY, IYFAR, ALOC, ALAT, ILCNG, IQUAD, IPAGE
COMMON/SOLH/TAIP, TOPT, ILOCAL, ZLAT, MDIR, MVFL, TSEA, VISR, CFRA, EMISS,
101, TCC, TAS, TSC, TTRN, QDIR, QSC, CONV, MREL, AZH, CTRANS, SOLARA, ZENITH, RH
COMMON/PRPL/KK, KMONTH, AYFAR, NOPLT
COMMON/STATV/M1, M2, M3, M4, M5, M6, NA, NB, NC, NF, NF, NS, NT, LCN, LD, LN
COMMON/SKPR/ISFAS, CHIT, RAC, SKYT, CRA1, CRA2, CRA3, CLO1, CLO2, CLO3
DIMENSION CRA1(6), CRA2(6), CRA3(6), CLC1(30), CLO2(30), CLO3(30)
DIMENSION CCOV(10), IWIN(4), ISPF(4), ISUM(4), IMON(12), KMON(12)
DIMENSION M1(79), M2(79), M3(79), M4(79), M5(79), M6(79), NA(79), NB(79),
1NC(79), NF(79), NF(79), TMOD(36), NS(79), NT(79), TEMP(79), TLIST(79)
DATA P/O.C1745/
DATA CCOV/0., 0.10, 0.25, 0.40, 0.50, 0.60, 0.75, 0.90, 1.0, 1.0/
DATA TMOD/10., 5., 4., 3.6, 3.2, 2.8, 2.4, 2.0, 1.8, 1.6, 1.4, 1.2, 1.0, 0.9,
10.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1, 0.0, -0.2, -0.4, -0.6, -0.8, -1.0, -1.4,
1-1.8, -2.2, -2.6, -3.0, -4.0, -5.0, -10.0/
DATA TLIST/60., 55., 50., 45., 40., 35., 30., 27., 24., 21., 18., 16., 15., 14.,
11., 13., 12., 11., 10., 9.5, 9., 8.5, 8.0, 7.5, 7.0, 6.5, 6.0, 5.5, 5.0, 4.6, 4.2,
13.8, 3.4, 3.0, 2.8, 2.6, 2.4, 2.2, 2.0, 1.8, 1.6, 1.4, 1.2, 1.0, 0.8, 0.6, 0.4,
10.2, 0.0, -0.2, -0.4, -0.6, -0.8, -1.0, -1.2, -1.4, -1.6, -1.8, -2.0, -2.2, -2.4,
1-2.6, -2.8, -3.0, -3.4, -3.8, -4.2, -4.6, -5.0, -5.5, -6.0, -6.5, -7.0, -8.0,
1-8.0, -10.0, -12.0, -15.0, -20.0, -40.0/
DATA TEMP/25., 24., 23., 22., 21., 20., 19., 18., 17., 16., 15., 14., 13., 12.,
11., 10., 9., 8., 7., 6., 5., 4., 3., 2., 1., 0., -1., -2., -3., -4., -5., -6., -7.,
1-8., -9., -10., -11., -12., -13., -14., -15., -16., -17., -18., -19., -20., -21.,
1-22., -23., -24., -25., -26., -27., -28., -29., -30., -31., -32., -33., -34.,
1-35., -36., -37., -38., -39., -40., -41., -42., -43., -44., -45., -46., -47.,
1-48., -49., -50., -51., -52., -53./
DATA IWIN/1, 2, 11, 12/, ISPF/3, 4, 9, 10/, ISUM/5, 6, 7, 8/
CALL SPRSET(ICOUNT, 10)
K=1
ILINE=0
ICOUNT=0
ITAIL=0.
IPAGE=1
JDAY=1
ILAST=0
C CONTROLS OVER CALCULATION, PRINTING AND PLOTTING
READ 101, NOPPT, NOPLT, JMONTH, LMONTH, ICPT, KSEAS, NN, (KMON(J), J=1, NN)
101 FORMAT(7I5, 11I4)
C SINGLE ELEMENT METHOD THERMAL MODEL
READ 102, M1, PCPX, PCPX2, PCPX3, R1, R2, TINT, TINT2, TINT3, T1, T2
102 FORMAT(4F8.2, 2F6.2, 3F8.2, 2F6.2)
C SHIP VELOCITY, SOLAR PROPERTIES AND STACK MODEL

```

FIGURE B-2 MAIN ROUTINE OF PROGRAM ASIRCT

```

READ 103,SPEED,MCG,FMISS,SOLARA,MSK,TSK,S1
103 FORMAT(7F10.2)
RFLA7=90.
7F=99.
ZENITH=90.
WSLO=1E.0
WSLO1=WSLO-.5*(90.-70)
ZZ3=7P-WSLO1
F1=.02+.98*(1.-COS(P*ZZ3))**.5
A7M=RFLA7*MCG
DO 37 I=1,4
IF(KSEAS.GT.1)GO TO 31
IMON(I)=IWIN(I)
GO TO 37
31 IF(KSEAS.GT.2)GO TO 32
IMON(I)=ISPF(I)
GO TO 37
32 IF(KSEAS.GT.3)GO TO 34
IMON(I)=ISUM(I)
33 CONTINUE
GO TO 37
34 DO 38 I=1,AN
38 IMON(I)=KMCN(I)
37 PRINT 200,SPEED,MCG,ZENITH,RFLA7
200 FORMAT(1H1,* TARGET SPEED=*,F5.1,*KNCTS AT HEADING=*,F5.0,*DEG FRC
1M NORTH SHIP ELEMENT VARIABLES ZENITH=*,F5.0,*AZIMUTH FRCM BOW=
1*,F5.0,*DEGREES*)
PRINT 201,TINT,MT,RCPX,FMISS,SOLARA
201 FORMAT(1H,* INTERNAL TEMP=*,F5.1,*DEG C INTERNAL H.T.COEFF=*,F5.
1*,*WATTS/M2-C RCPC=*,F6.3,*WATT-M2/M2-C SURFACE EMISSIVITY=*,
1,F4.2,* SOLAR ABSORPTANCE=*,F4.2)
DO 3 I=1,79
M1(I)=0
M2(I)=0
M3(I)=0
M4(I)=0
M5(I)=0
M6(I)=0
MA(I)=0
MB(I)=0
MF(I)=0
NS(I)=0
NT(I)=0
3 NC(I)=0

```

```

      ISEAS=2
      IF (IMONTH.GE.5.AND.IMONTH.LE.10) ISEAS=1
      CALL SKRAD
      JSEAS=ISEAS
      DO 4 I=1,36
4    NF(I)=0
      LCN=0
      LP=0
      LC=0
5    READ(1,8) NUM,ALCC,ISEA,ITIME,IQUAD,ILAT,ILONG,IYEAR,IMONTH,IDAY,
      IICHT,ILOCAL,IWIND,AWINDS,VIS,IWFAT,AIRPRO,TAIR,TOPT,TSEA,ICOV,ICL
      IT,IIC,IMC,IMC,CHTY,MAVEN,SHELLH,AJUNK
8    FORMAT(I6,1X,A2,4I2,I4,1X,I3,4I3,1X,I2,F4.0,1X,F5.2,1X,I2,1X,F6.1,
      1X,F5.1,1X,2I2,3I2,F6.0,2(1X,F3.0),1X,A10)
      IF (ICOUNT.EQ.0) GO TO 10
      ICOUNT=0
      ILINE=77
      GO TO 5
10   CONTINUE
      IF (EOF(1)) 190,7
7    IF (IMONTH.EQ.LMONTH) GO TO 190
      IF (IMONTH.NE.IMON(K)) GO TO 5
6    IF (OTBL.NE.0.) GO TO 11
      WCLD=ILOCAL-12
      DTAB=1.0
      GO TO 5
11   AYFAP=IYFAP+1900
      ISEAS=2
      IF (IMONTH.GE.5.AND.IMONTH.LE.10) ISEAS=1
      IF (ISEAS.EQ.ISEAS) GO TO 12
      CALL SKRAD
      JSEAS=ISEAS
12   ALAT=ILAT
      PLAT=PLAT
      WVFL=AWINDS
      WPIP=10*IWIND
      KCOV=ICOV+1
      CFRA=CCOV(KCOV)
      VIS2=VIS
      CALL CLDTR(ILC,IMC,IMC,IWFAT,CTrans,COND,RCOFF)
      ILINE=ILINE+1
      IF (IDAY.EQ.JDAY) GO TO 20
      OSUN=0.
      OSOD=0.0

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```

      TIN=TAIP
      CALL NEWDAY(IILIN,ZSOL,SUNR,SNSET)
20  JDAY=JDAY
21  HOUR=ILOCAL-12
      LCN=LCN+1
      DTAU=HOUR-HOLD
      HCOL=HOUR
      IF (DTAU.LT.0.) DTAU=DTAU+12.0
      IF (DTAU.EQ.0.) GO TO 5
      CALL SOLAR(HOUR,ZSOL,SPEED,HOG,SUNR,SNSET,QSUN,DTAU,DTIN)
      QSOL=(QSUN+QSDC)*DTIN/(2.0*PCPY)
      QSDC=QSUN
      HINT=HI*DTAU/PCPY
      HRAIN=RCCFF*DTAU/PCPY
      HCOL=CONV*DTAU/PCPY
      TI=TAIR
      TT=(TIN+QSOL+HCOL*TAIP+HRAIN*TAIR+HINT*TINT)/(1.+HCOL+HRAIN+HINT)
98  A1=DTAU/PCPY
      A2=DTAU/PCPY2
      A3=DTAU/PCPY3
      F=(QSUN+QSDC)/2.+(CONV+RCCFF)*TAIR+HI*TINT
      G=CONV+RCCFF+HI
      HSTK=HCK*DTAU/PCPY
      TC1=R1*(A2-A1)*(F-G*TI)/(1.+G*(A1+A2)+A1*A2*G*G)+R2*(A3-A1)*(F-G*
1  TI)/(1.+G*(A1+A3)+A1*A3*G*G)
      BB=HINT/(1.+HCOL+HRAIN+HINT)
      TC2=T1*BB*(TINT2-TINT)+T2*BB*(TINT3-TINT)
      TC3=S1*HSTK*((HCOL+HRAIN+1.)*(TSK-TAIF)-QSOL)
1  1/((HCOL+HRAIN+HSTK)*(HCOL+HRAIN+1.))
      TC=TC1+TC2+TC3
      TT=TT+TC
      TT=EMISS*TT+(1.-EMISS)*TAIP
      TIN=TT
      DO 47 L=1,76
      JL=L
      IF (TC.GT.T*OD(L)) GO TO 98
97  CONTINUE
88  NE(JL)=NE(JL)+1
      CALL TRSKY(CFPA,PM,MVFL,TAIR,TEMP,NB)
      DO 40 J=1,79
      J=J
      IF (TT.GT.TLIST(J)) GO TO 41
40  CONTINUE
41  NA(J)=NA(J)+1

```

```

TRGD=F1*SKYT+(1.-F1)*TSEA
DO 25 I=1,79
  J=I
  IF (TRGD.GT.TLIST(I))GO TO 26
25 CONTINUE
26 NS(I)=NS(J)+1
  TCON=TT-TRGD
  DO 42 I=1,79
    J=I
    IF (TCON.GT.TLIST(I))GO TO 43
  42 CONTINUE
  43 NT(I)=NT(J)+1
    IF (HOUR.LT.SUNR.OP.HOUR.GT.SNSFT)GO TO 30
    LC=LC+1
    DO 44 I=1,79
      J=I
      IF (TCON.GT.TLIST(I))GO TO 45
    44 CONTINUE
    45 NC(J)=NC(J)+1
      IF (HOUR.LT.-7.OP.HOUR.GT.7)GO TO 47
      CALL CONHR(J,NC,HOUR,M1,M2,M3,M4,M5,M6)
      GO TO 47
  47 LN=LN+1
    DO 35 I=1,79
      J=I
      IF (TCON.GT.TLIST(I))GO TO 36
    35 CONTINUE
    36 NF(J)=NF(J)+1
C CONVERT RADIANCE FUNCTION TO RADIANCE
  47 RAD=0.4*PAQ
    IF (NOPRT.EQ.1)GO TO 48
    IF (HOUR.LT.SUNR.OP.HOUR.GT.SNSFT)GO TO 46
    IF (HOUR.LE.0.)HOUR=HOUR+12.0
    PRINT 210,HOUR,TCC,TAS,TSC,TTON,7DIR,QSC,QSUN,WVFL,WDIR,WREL,CONV,
1COND,RCOFF,TAIR,TSEA,TT,TC,RAD,SKYT,TRGD,TCON
210 FORMAT(1H ,F4.0,4F6.3,F7.2,2F7.2,F4.0,F6.0,F5.0,F7.2,1X,A8,F6.0,
1F6.2,F5.2,F7.2,3F6.2)
    GO TO 48
  46 IF (HOUR.LE.0.)HOUR=HOUR+12.0
    PRINT 211,HOUR,WVFL,WDIR,WREL,CONV,COND,RCOFF,TAIR,TSEA,TT,TC,RAD,
1SKYT,TRGD,TCON
211 FORMAT(1H ,F4.0,42X,F7.0,F6.0,F5.0,F7.2,1X,A8,F6.0,3F6.2,F5.2,
1F7.2,3F6.2)
  48 IF (IMONTH.EQ.JMONTH)GO TO 5

```

```

JMONTH=IMONTH
K=K+1
IF(IOPT.EQ.0) GO TO 5
99 CONTINUE
KMONTH=JMONTH-1
CALL ANAL(MOD,TINT,ROPR,TMOD,TLIST,TEMP)
IF(ILAST.EQ.1) GO TO 199
GO TO 6
190 ILAST=1
GO TO 99
199 CONTINUE
STOP
END

```

```

SUBROUTINE SKRAD
COMMON/SKPR/ISFAS,CHIT,PAD,SKYT,CRA1,CRA2,CRA3,CLD1,CLD2,CLD3
DIMENSION CRA1(6),CRA2(6),CRA3(6),CLD1(30),CLD2(30),CLD3(30)
DIMENSION CSUM1(6),CSUM2(6),CSUM3(6),CHIN1(6),CHIN2(6),CHIN3(6),
1COSM1(30),COSM2(30),COSM3(30),CWM1(30),CWM2(30),CWM3(30)
DATA CSUM1/40.6516,41.2164,43.2315,47.4141,59.7090,79.1600/
DATA CSUM2/40.6213,41.1519,43.0577,47.0070,58.9722,78.0678/
DATA CSUM3/40.5866,41.0795,42.9625,46.5470,57.9060,77.9032/
DATA COSM1/66.9650,66.2204,67.1301,67.7150,70.1194,77.5559,69.4615,
162.5022,69.6312,70.0005,71.6061,77.5494,72.1438,72.1709,72.2379,
172.4354,73.3032,77.5712,74.9496,74.9560,74.9765,75.0371,75.3178,
177.5554,76.9320,76.3400,76.9432,76.9528,76.9901,77.6636/
DATA COSM2/66.9616,66.3194,67.0999,67.6323,69.8536,77.4214,69.4593,
163.4947,69.6095,69.9460,71.3941,77.4176,72.1480,72.1664,72.2242,
172.3066,72.1664,72.4474,74.9400,74.9545,74.9717,75.0233,75.2649,
177.4384,76.9389,76.3327,76.9424,76.9504,76.9896,77.5954/
DATA COSM3/66.9562,66.9097,67.0674,67.5415,69.5585,77.2554,66.4550,
162.4871,69.5850,69.8801,71.1690,77.2506,72.1461,72.1619,72.2102,
172.3564,73.0225,77.2877,74.9495,74.9531,74.9671,75.0100,75.2132,
177.2942,76.9348,76.9325,76.9417,76.9483,76.9802,77.5246/
DATA CHIN1/21.9527,22.0754,26.5491,33.8458,53.8748,78.1901/
DATA CHIN2/21.8680,22.8004,26.0930,32.8275,51.9976,78.0453/
DATA CHIN3/21.7841,22.6318,25.6508,31.9203,50.0894,77.8084/
DATA CWM1/64.4360,64.5260,64.9152,65.6404,68.0242,77.5925,67.9924,
168.0459,68.2219,68.7255,70.8041,77.5716,71.4325,71.4599,71.5441,
171.7920,72.8631,77.5935,74.7161,74.7236,74.7478,74.9193,75.1470,
177.5765,76.8949,76.8960,76.8996,76.9103,76.9617,77.6759/
DATA CWM2/64.4269,64.5052,64.7522,65.4705,69.4058,77.3958,67.9862,
169.0326,68.1789,68.6058,70.4178,77.3820,71.4291,71.4508,71.5123,
171.7221,72.6216,77.4156,74.7150,74.7210,74.7400,74.7965,75.0605,
177.4064,76.8947,76.8956,76.8984,76.9068,76.9474,77.5775/
DATA CWM3/64.4185,64.8865,64.6961,65.3146,67.9108,77.1674,67.9802,
169.0205,68.1417,68.5039,70.0734,77.1701,71.4262,71.4441,71.4984,
171.6631,72.4122,77.2088,74.7143,74.7121,74.7339,74.7788,74.9920,
177.2248,76.8946,76.8954,76.8976,76.9043,76.9373,77.4929/
IF (ISFAS.EQ.2) GO TO 21
DO 10 I=1,6
CRA1(I)=CSUM1(I)
CRA2(I)=CSUM2(I)
10 CRA3(I)=CSUM3(I)

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FIGURE B-3 SUBROUTINE SKRAD OF PROGRAM ASIRCT

```
DO 15 I=1,30
  CLD1(I)=COSM1(I)
  CLD2(I)=COSM2(I)
15 CLD3(I)=COSM3(I)
  GO TO 40
20 DO 30 I=1,6
  CPA1(I)=CWIN1(I)
  CPA2(I)=CWIN2(I)
30 CPA3(I)=CWIN3(I)
  DO 35 I=1,30
  CLD1(I)=CDWN1(I)
  CLD2(I)=CDWN2(I)
35 CLD3(I)=CDWN3(I)
40 CONTINUE
  GETJEN
  END
```

```

SUBROUTINE CLDTR(ILC,IMC,IMC,IWFAT,CTRANS,COND,RCOEF)
DIMENSION LITR(15),IMFD(14),IHFV(11),LITD(4),JMFD(3),JHEV(3)
DIMENSION WEATH(7)
DATA WEATH/8HNO PREC ,8HPREC WHR,8HFOG/ICFF,8HNR177LF ,8HRAIN
18HSNOW ,8HSHOWERS /
DATA LITR/60,61,66,6A,70,71,76,78,80,83,85,87,89,91,93/
DATA IMFD/62,63,72,73,77,81,84,86,89,90,92,94,95,96/
DATA IHFV/64,65,67,69,74,75,79,82,97,98,99/
DATA LITD/50,51,56,5A/
DATA JMFD/52,53,57/
DATA JHEV/54,55,59/
IF(ILC.EQ.0)GO TO 50
IF(ILC.GT.2)GO TO 20
CTRANS=0.6
GO TO A0
20 IF(ILC.GT.3)GO TO 25
CTRANS=0.50
GO TO A0
25 IF(ILC.GT.5)GO TO 30
CTRANS=0.33
GO TO A0
30 IF(ILC.GT.7)GO TO 35
CTRANS=0.25
GO TO A0
35 IF(ILC.GT.8)GO TO 40
CTRANS=0.2
GO TO A0
40 CTRANS=0.2
GO TO A0
50 IF(IMC.EQ.0)GO TO 60
IF(IMC.GT.2)GO TO 55
CTRANS=0.41
GO TO A0
55 CTRANS=0.49
GO TO A0
60 IF(IMC.GT.0)GO TO 65
CTRANS=1.00
GO TO A0
65 IF(IMC.GT.7)GO TO 70
CTRANS=0.83
GO TO A0

```

FIGURE B-4 SUBROUTINE CLDTR OF PROGRAM ASIRCT

```

70 IF(IHC.GT.8)GO TO 75
   CTPANS=0.74
   GO TO 80
75 CTPANS=0.65
90 CONTINUE
   IF(IWFAT.GT.19)GO TO 85
   COND=WFATH(1)
   GO TO 120
85 IF(IWFAT.GT.39)GO TO 90
   COND=WFATH(2)
   GO TO 120
90 IF(IWFAT.GT.49)GO TO 95
   COND=WFATH(3)
   GO TO 120
95 IF(IWFAT.GT.59)GO TO 105
   COND=WFATH(4)
   GO TO 120
105 IF(IWFAT.GT.69)GO TO 110
   COND=WFATH(5)
   GO TO 120
110 IF(IWFAT.GT.79)GO TO 115
   COND=WFATH(6)
   GO TO 120
115 COND=WFATH(7)
120 RCOFF=0.
   IF(IWFAT.LT.50)GO TO 150
   IF(IWFAT.GT.59)GO TO 130
   DO 121 I=1,4
   IF(IWFAT.EQ.LIYD(I))GO TO 122
121 CONTINUE
   GO TO 123
122 RCOFF=12.
   GO TO 150
123 DO 124 I=1,3
   IF(IWFAT.EQ.JMFD(I))GO TO 125
124 CONTINUE
   GO TO 126
125 RCOFF=20.
   GO TO 150

```

```
126 DO 127 I=1,3  
    IF(IWFAT.EQ.JHEV(I))GO TO 128  
127 CONTINUE  
128 PCOFF=30.  
    GO TO 150  
130 DO 135 J=1,15  
    IF(IWFAT.EQ.LITR(J))GO TO 136  
135 CONTINUE  
    GO TO 139  
136 PCOFF=80.  
    GO TO 150  
139 DO 140 J=1,14  
    IF(IWFAT.EQ.IMED(J))GO TO 142  
140 CONTINUE  
    GO TO 144  
142 PCOFF=135.  
    GO TO 150  
144 DO 145 J=1,11  
    IF(IWFAT.EQ.IHEV(J))GO TO 148  
145 CONTINUE  
148 PCOFF=200.  
150 CONTINUE  
    RETURN  
    END
```

```

SUBROUTINE NEWDAY (ILINE,ZSOL,SUNR,SNSET)
COMMON/DAYH/MONTH, IDAY, IYEAR, ALOC, ALAT, ILONG, IQUAD, IPAGE
COMMON/PPPL/KK, KMONTH, AYEAR, NOPLT
DIMENSION DECL(49)
DATA P/C.31745/
DATA DECL/-1388.,-1340.,-1275.,-1193.,-1038.,-814.,-775.,-627.,-47
11.,-319.,-145.,21.,256.,416.,570.,717.,891.,1013.,1121.,1214.,1317
1.,1367.,1397.,1407.,1392.,1354.,1299.,1225.,1092.,981.,857.,722.,
1513.,358.,199.,36.,-17.,-336.,-495.,-648.,-852.,-982.,-1098.,
1-1199.,-1274.,-1358.,-1394.,-1407.,-1388./
II=4*(MONTH-1)
IJ=(IDAY-1)/7
IK=II+IJ+1
IF (IDAY.GE.20) IK=IK-1
FRAC=IDAY-7*IJ-1
ZSOL=DECL(IK)+10DECL(IK+1)-DECL(IK))* (FRAC)/7.
ZSOL=ZSOL/60.
Z1=SIN(P*ALAT)
Z2=COS(P*ALAT)
A=-SIN(P*ZSOL)*SIN(P*ALAT)/(COS(P*ZSOL)*COS(P*ALAT))
AA=ACOS(A)/P
SUNR=-AA/15.*12.
SNSET=24.-SUNR
JLAT=ALAT
IF (NOPLT.EQ.1) GO TO 20
PRINT 160,IMONTH,IDAY,IYEAR,ALOC,JLAT,ILONG,IQUAD,SUNR,SNSET
160 FORMAT(1H),* DATE IS*,I2,*/*,I2,*/*,I4,* WEATHER SHIP*,A2,3X,
1*AT LATITUDE *,I2,3X,*AND LONGITUDE*,I2,* (QUADRANT*,I2,*) SUN RIS
1E AT*,F5.2,*HOURS SUNSET AT*,F5.2,*HOURS*)
IF (ILINE.GT.37) IPAGE=1
IF (IPAGE.EQ.0) GO TO 20
PRINT 215
215 FORMAT(1H),* CLOUD AERO SCAT TOTAL DIR. INDIR SOLAR WIND
1DIRECT REL CONV WEATHER RAIN AIR T SEA T SHIP CORR. SKY A SKY
1 T PACKET CONTR*)
PRINT 220
220 FORMAT(1H),* TIM TRANS TRANS ABSOR TRANS SOLAR SOLAR ABSOR SPEED
1CG-NTH WIND COEFF CODE COEFF DEG C DEG C EMP DEG C FAD 12 DEG
1 C DEG C DEG C*)
ILINE=0
IPAGE=0
20 CONTINUE
SNSET=SNSET-12.
SUNR=SUNR-12.
RETURN
END

```

FIGURE B-5 SUBROUTINE NEWDAY OF PROGRAM ASIRCT

```

SUBROUTINE SOLAR(HOUR,ZSOL,SPEED,HOG,SUNR,SNSET,OSUN,DTAU,DTIM)
COMMON/SOLH/TAIR,TDPT,ILOCAL,ZLAT,WDIR,WVEL,TSEA,VISR,CFRA,EMISS,
1G1,TCG,TAS,TSC,TTRN,QDIR,OSC,CONV,WREL,AZM,CTRANS,SOLARA,ZENITH,RH
DATA P/2.31745/
AA=273.15/(273.15+TAIR)
WSAT=AA*EXP(18.9766-14.9595*AA-2.4388*AA*AA)
AA=273.15/(273.15+TDPT)
WCON=AA*EXP(18.9766-14.9595*AA-2.4388*AA*AA)
RH=100.*WCON/WSAT
HUMID=WSAT*RH/100.
Z2 = SIN(P*ZSOL)
Z4 = COS(P*ZSOL)
Z1=SIN(P*ZLAT)
Z3=COS(P*ZLAT)
Z5 = COS(P*15.*HOUR)
Z6 = Z1*Z2+Z3*Z4*Z5
SOL7 = (ACOS(Z6))/P
W1 = WVEL*SIN(P*WDIR)
W2 = WVEL*COS(P*WDIR)
W3 = SPEED*SIN(P*HOG)+W1
W4 = SPEED*COS(P*HOG)+W2
WREL = SQRT(W3**2 + W4**2)
CONV=3.5625*WREL**3.6
IF(CONV.LT.6)CONV=6.
C CONVERT WIND SPEEDS FROM KNOTS TO METERS/SEC
WVEL=WVEL/2.0
WREL=WREL/2.0
DTIM=DTAU
IF (SOL7.LT.89.) 30,100
30 Y1=COS(P*ZLAT)*SIN(P*ZSOL)
Y2=COS(P*ZSOL)*SIN(P*ZLAT)
Y3=Y1-Y2**5
Y=COS(P*(90.-SOL7))
50 SOLA7=ACOS(Y3/X)/P
IF(HOUR.GT.3.)SOLA7=363.-SOLA7
C SOLAR HEAT LOAD
C CALCULATION OF SLANT PATH EQUIVALENT AIR MASS
IF (SOL7.LT.60.) 51,52
51 A = 1./COS(P*SOLZ)
A1 = A
GO TO 53
52 A = 1./COS(P*(SOL7 - .3))
A1 = 1./COS(P*(SOL7-.4))

```

CALT02
CALT02

CALT03
CALT03
CALT10
CALT10
CALT10
CALT11
CALT11

CALT03

CALT04
CALT04
CALT04
CALT04
CALT05
CALT05
CALT05
CALT05

FIGURE B-6 SUBROUTINE SOLAR OF PROGRAM ASIRCT

```

53 CONTINUE
  MW=1.5*WU*ID
  TMS=EXP((.441+.1623*WU)*(EXP(-.193*A)-1.))
  ARW=EXP(-2.5/((MW*A1)**.0975))
  TSC=TMS-ARW
  TAS = EXP(-5. *A1/VISR)
  TS = 1. - ((TMS+TAS)/2.)
  Z7 = SIN(P*SOLZ)
  B = (Z6**CFPA)*(1.-CFPA**2)
  TCC = 1. - (1.-B)*(1.-CTANS)
  TTRN=TCC*TAS*TSC
  QDIR=135J.*TTRN
  QSC=QDIR*TS
61 D1=COS(P*(AZH-SOLAZ))
  D2=SIN(P*ZENITH)
  D3=COS(P*ZENITH)
  D4 = 77*D1*D2+D3*76
  IF (D4.LT.0.) D4=0.
  A2=.5*ARC(AZH-SOLAZ)
  D5 = .35*(1. + 2.*Z7*(COS(P*A2)**2))
  IF (QSUN.GT.0.) GO TO 42
  DTIM=HOUR-SUNF
*2 QSUN=SOLAR*A*(L4*QDIR+D5*QSC)
  RETURN
C SUN BELOW HORIZON
103 TCC=0.
  TAS=0.
  TSC=0.
  TTRN=0.
  QDIR=0.
  QSC=0.
  IF (QSUN.EQ.0.) GO TO 110
  DTIM=HOUR-SUNSET
  QSUN=0.0
110 CONTINUE
  RETURN
END

```

CALT05
CALT05
CALT05
CALT05

CALT05
CALT05
CALT06
CALT06
CALT06

CALT08
CALT08

CALT08

CALT09

```

SUBROUTINE TRSKY (CFRA,RH,WS,TAIR,TEMP,NR)
COMMON/SKPF/ISFAS,CHIT,RAD,SKYT,CRA1,CRA2,CRA3,CLO1,CLO2,CLO3
DIMENSION CRA1(6),CRA2(6),CRA3(6),CLO1(30),CLO2(30),CLO3(30),
1APH(3),ACHT(5),AWS(6),RADL(6),RADU(6),RCRL(6),RCRU(6)
DIMENSION HBRD(79),TEMP(79),CCOV(10),NR(79)
DATA CCOV/0.,.1.,.25.,.4.,.5.,.6.,.75.,.9.,1.0,1.0/
DATA APH/100.,.95.,.60./
DATA ACHT/1750.,1250.,900.,400.,150./
DATA AWS/0.,.5.,.10.,.15.,.20.,.30.,.40./
DATA HBRD/101.6676,99.9875,94.3248,96.6744,95.0512,93.4402,91.8464
1.90,2697.48,7100.47,1673.45,6417.84,1329.87,6411.81,1660.79,7078.
179.2662,76.3414,75.4331,74.0415,72.4663,71.3076,69.9653,68.6393,
167.3296,66.0361,64.7589,63.4975,62.2523,61.0230,59.8097,58.6121,
157.4323,56.2642,55.1137,53.9797,52.8592,51.7551,50.6663,49.5927,
148.5343,47.4910,46.4627,45.4492,44.4507,43.4669,42.4977,41.5431,
140.6030,39.6773,38.2218,37.7659,37.4648,36.9857,36.1168,35.2617,
134.4205,33.5931,32.7793,31.9791,31.1923,30.4189,29.6588,28.9118,
129.1773,27.4569,26.8534,25.3716,24.7004,24.0426,23.3971,22.7637,
122.1423,21.5332,20.9359,20.3501,19.7661,19.2136,18.6624,18.1226/
DO 10 I=1,5
II=I
IF (CHIT.CF.ACHT(I)) GO TO 15
10 CONTINUE
15 T=1+5*(II-1)
II=I+5
IF (RH.LT.95.) GO TO 25
IF (RH.EQ.95) GO TO 30
IF (RH.EQ.100.) GO TO 35
J=0
DO 20 N=1,II
J=J+1
RADL(J)=CLO2(N)
RADU(J)=CLO1(N)
RCRL(J)=CRA2(J)
20 RCRU(J)=CRA1(J)
JJ=J
GO TO 40
25 J=0

```

FIGURE B-7 SUBROUTINE TRSKY OF PROGRAM ASIRCT

```

20 20 N=I,I1
   J=J+1
   RAOL(J)=CLO1(N)
   RADU(J)=CLO2(N)
   RCRL(J)=CRA1(J)
21 RCRU(J)=CRA2(J)
   JJ=3
   GO TO 40
30 J=0
   GO 32 N=I,I1
   J=J+1
   RAOL(J)=CLO2(N)
32 RCRL(J)=CRA2(J)
   JJ=1
   GO 30 40
35 J=0
   GO 36 N=I,I1
   J=J+1
   RAOL(J)=CLO1(N)
36 RCRL(J)=CRA1(J)
   JJ=1
40 GO 45 L=1,6
   LL=L
   IF (WS.LE.AWS(LL)) GO TO 50
45 CONTINUE
50 IF (LL.EQ.1.OR.WS.GT.30.) GO TO 55
   PA=RAOL(LL-1)*(RAOL(LL)-RAOL(LL-1))*(WS-AWS(LL-1))/(AWS(LL)-
1 AWS(LL-1))
   PCA=RCRL(LL-1)*(RCRL(LL)-RCRL(LL-1))*(WS-AWS(LL-1))/(AWS(LL)-
1 AWS(LL-1))
   GO TO 56
55 PA=RAOL(LL)
   PCA=RCRL(LL)
56 IF (JJ.EQ.1) GO TO 65
   IF (LL.EQ.1.OR.WS.GT.30.) GO TO 58
   QA=RADU(LL-1)*(RADU(LL)-RADU(LL-1))*(WS-AWS(LL-1))/(AWS(LL)-
1 AWS(LL-1))
   PCQ=RCRU(LL-1)*(RCRU(LL)-RCRU(LL-1))*(WS-AWS(LL-1))/(AWS(LL)-
1 AWS(LL-1))
   GO TO 60

```

```

53 R3=RA0J(LL)
   RC3=RC0J(LL)
60 R4=R3-RA*(RH-ARH(JJ))/(ARH(JJ-1)-ARH(JJ))
   PC4=PC3+RC3-PCA*(RH-APH(JJ))/(APH(JJ-1)-ARH(JJ))
65 F1=(C.S*CFRA)*(1.-CFRA*CFRA)
   PAC=PA*(1.-F1)+F1*PCA
   CC 71 I=1.79
   J=I
   IF (PAC.GT.BBRD(I)) GO TO 72
71 CONTINUE
72 QQR=(TEMP(J-1)-TEMP(J))*(RA0-BB0(J))/(BB0(J-1)-BB0(J))
   SKYT=TEMP(J)+QQR
   A0J=TAIR-10.
   IADJ=A0J
   RHA=A0J-IADJ
   SKYT=SKYT+A0J
   J=J-IADJ
   B0UP=B0A+Q0J
   IF (B0UP.GT.1.0) J=J-1
   IF (SKYT.LT.TEMP(J)) J=J-1
   NR(J)=NR(J)+1
   GETURN
END

```

```

SUBROUTINE CONMR(J,NC,NQUP,M1,M2,M3,M4,M5,M6)
DIMENSION M1(79),M2(79),M3(79),M4(79),M5(79),M6(79)
ITIM=NQUP+1.
GO TO(1,2,3,4,5,6)ITIM
1 M1(J)=M1(J)+1
GO TO A
2 M2(J)=M2(J)+1
GO TO A
3 M3(J)=M3(J)+1
GO TO A
4 M4(J)=M4(J)+1
GO TO A
5 M5(J)=M5(J)+1
GO TO A
6 M6(J)=M6(J)+1
A CONTINUE
RETURN
END

```

FIGURE B-8 SUBROUTINE CONMR OF PROGRAM ASIRCT

```

SUBROUTINE ANAL(MDG,TINT,RCPX,THDG,TLIST,TEMP)
COMMON/PRPL/KK,KMONTH,AYEAR,NOPLT
COMMON/STATV/M1,M2,M3,M4,M5,M6,NA,NB,NC,NE,NF,NS,NT,LCN,LD,LN
DIMENSION M1(79),M2(79),M3(79),M4(79),M5(79),M6(79),NA(79),NB(79),
INC(79),NE(79),NF(79),THDG(36),NS(79),NT(79),TEMP(79),TLIST(79)
DIMENSION TSHD(10),TSKY(10),TDCON(10),TNCON(10),TADD(10),TTEN(10),
ITFLN(10),TTWL(10),TONE(10),TTWO(10),TTW*(10),TTCON(10),TRCK(10)
KK=0
N1=0
N2=0
N3=0
N4=0
N5=0
N6=0
AYEAR=AYEAR
PRINT 213,KMONTH,AYEAR,RCPX,TINT,M3
213 FORMAT(1H1,* PROBABILITY OF OBSERVING SHIP TEMPERATURES MONTH=*
1,12,* YEAR=*,14,* RCPX=*,F6.2,* INT TEMP=*,F5.2,*DFG-C HE
1ADING=*,F5.2)
KK=KK+1
CALL SORTINA,LCN,TLIST,TSHD)
PRINT 214
214 FORMAT(1H1,////)
PRINT 221
221 FORMAT(1H1,* PROBABILITY OF OBSERVING SKY TEMPERATURES*)
KK=KK+1
CALL SORTIND,LCN,TEMP,TSKY)
PRINT 225
225 FORMAT(1H1,* PROBABILITY OF OBSERVING BACKGROUND TEMPERATURES*)
KK=KK+1
CALL SORTINC,LCN,TLIST,TRCK)
PRINT 222
222 FORMAT(1H1,* PROBABILITY OF OBSERVING CONTRAST TEMPERATURES DURING
16 DAYLIGHT HOURS*)
KK=KK+1
CALL SORTINC,LD,TLIST,TDCON)
PRINT 224,KMONTH,AYEAR
224 FORMAT(1H1,* PROBABILITY OF OBSERVING CONTRAST TEMPERATURES DURING
16 NIGHTTIME HOURS MONTH=*,12,* YEAR=*,14)
KK=KK+1
CALL SORTINF,LN,TLIST,TNCON)
KK=KK+1

```

FIGURE B-9 SUBROUTINE ANAL OF PROGRAM ASIRCT

```

PRINT 227
227 FORMAT(1H),* PROBABILITY OF OBSERVING TOTAL CONTRAST TEMPERATURE*
1)
CALL SORT(M1,LCN,TLIST,TTCON)
PRINT 228
228 FORMAT(1H),* PROBABILITY OF OBSERVING TEMPERATURE MODIFICATION*
KK=KK+1
CALL SORT(MF,LCN,TMOD,TADD)
PRINT 230,KMONTH,IYEAR
230 FORMAT(1H),* CONTRAST TEMPERATURES ON HOURLY BASIS MONTH=*,I2,
1* IYEAR=*,I4)
DO 91 KJ=1,79
IF (M1(KJ).GT.0) N1=N1+M1(KJ)
IF (M2(KJ).GT.0) N2=N2+M2(KJ)
IF (M3(KJ).GT.0) N3=N3+M3(KJ)
IF (M4(KJ).GT.0) N4=N4+M4(KJ)
IF (M5(KJ).GT.0) N5=N5+M5(KJ)
91 IF (M6(KJ).GT.0) N6=N6+M6(KJ)
PRINT 231
231 FORMAT(1H),* 10.A.M.*)
KK=KK+1
CALL SORT(M1,N1,TLIST,TTEN)
KK=KK+1
PRINT 232
232 FORMAT(1H),* 11.A.M.*)
CALL SORT(M2,N2,TLIST,TFEN)
PRINT 233
233 FORMAT(1H),* 12.NOON*)
CALL SORT(M3,N3,TLIST,TTWL)
PRINT 234
234 FORMAT(1H),* 1.P.M.*)
CALL SORT(M4,N4,TLIST,TFNE)
PRINT 235
235 FORMAT(1H),* 2.P.M.*)
CALL SORT(M5,N5,TLIST,TTWG)
PRINT 236
236 FORMAT(1H),* 3.P.M.*)
CALL SORT(M6,N6,TLIST,TTWR)
PRINT 240
240 FORMAT(1H),* PROB SKY TEMP SWIP TEN BACKGRND MODIFIC DAY CONT
1NIGHT CN TOTAL CN 10AM CN 11AM CN 12NN CN 1PM CN 2PM CN
1 3PM CN*)

```

```

AA=C.95
DO 92 I=1,10
PRINT 242,AA,TSKY(I),TSHP(I),TFCR(I),TADD(I),TOCON(I),TNCON(I),
1TTCON(I),TTFH(I),TELN(I),TTLN(I),TONE(I),TTWO(I),TTHR(I)
242 FORMAT(1H,56.2,4F9.2,2X,3F9.2,4X,6F9.2)
A=I
AA=1.0-0.1*A
92 CONTINUE
PRINT 250
250 FORMAT(1H1)
LN=0
LI=0
LCN=C
RETURN
END

```

```

SUBROUTINE SORT(ND,NUM,TEMP,STAT)
COMMON/PPDL/KK,KMONTH,AYEAR,NOPLT
DIMENSION ND(79),PROB(79),TEMP(79),X(40),Y(40),OPT(10),STAT(10)
DATA OPT/0.95,0.90,0.80,0.70,0.60,0.50,0.40,0.30,0.20,0.10/
LL=79
AM=AYEAR
AMON=KMONTH
DO 5 M=1,LL
  IN=M
  IF (ND(IN).GT.0) GO TO 6
5 CONTINUE
6 DO 10 N=1,LL
  LN=LL+1-N
  IF (ND(LN).GT.0) GO TO 12
10 CONTINUE
12 AM=NUM
  PA=ND(IN)
  AN=LN-1
  DO 20 L=IN,NN
    PROB(L)=(AM-PA)/AM
    PA=PA+ND(L+1)
20 CONTINUE
  PROB(LN)=0.0
  PRINT 100
100 FORMAT(14,'*      TEMP      NUMBER      PROB VALUE      TEMP      NUMBER      OR
100 VALUE      TEMP      NUMBER      PROB VALUE      TEMP      NUMBER      OR
100 VALUE*)
  PRINT 101
101 FORMAT(14,'*      DEG-C      AT TEMP      OR LESS      DEG-C      AT TEMP      OR
1 LESS      DEG-C      AT TEMP      OR LESS      DEG-C      AT TEMP      OR
1 LESS*)
35 L=1
  NM=LN-IN
  IF (NM.GE.4) L=2
  IK=(LN-IN+4)/4
  IJ=IN
  IM=IK
  DO 40 K=1,IK
    PRINT 105,(TEMP(I),ND(I),PROB(I),I*IJ,LN,IM)
    IJ=IJ+1
105 FORMAT(14,'* (F8.2,I3,F12.3,4X)')
40 CONTINUE

```

FIGURE B-10 SUBROUTINE SORT OF PROGRAM ASIRCT

```

      IF (IN.EQ.1) IN=IN+1
      DO 34 I=1,10
      DO 36 K=IN,NN
      IF (PROB(K).LT.DPT(I)) GO TO 33
36 CONTINUE
33 STAT(I)=TEMP(K)+(TEMP(K-1)-TEMP(K))*(DPT(I)-PROB(K))/(PROB(K-1)
  1-PROB(K))
34 CONTINUE
      IF (NOPLY.EQ.1) GO TO 55
      IF (KK.GT.3) GO TO 37
      T1=3J.
      T2=-2L.
      GO TO 43
37 IF (KK.GT.6) GO TO 41
      T1=25.J
      T2=-5.J
      GO TO 43
41 IF (KK.GT.7) GO TO 42
      T1=2.E
      T2=-6.5
      GO TO 43
42 T1=25.J
      T2=J.
43 J=0
      N=.
      DO 44 I=IN,LN
      IF (TEMP(I).GT.T1) GO TO 32
      IF (TEMP(I).LT.T2) GO TO 32
      IF (J.EQ.1) GO TO 32
      N=N+1
      X(N)=TEMP(I)
      Y(N)=PROB(I)
      J=J+1
      GO TO 44
44 J=0
      CONTINUE
      IF (KK.EQ.1) GO TO 45
      IF (KK.EQ.4) GO TO 49
      IF (KK.EQ.7.OR.KK.EQ.8) GO TO 46
      CALL CALCH1(-X,X,Y,3)
      GO TO 55

```

```

45 CALL CALCH1(N,X,Y,0,T2,T1,0.0,1.00,10.0,8.00,37MSKY SHIP BACKGND
   TEMPERATURE YEAR=,37,17HTEMPERATURE DEG C,17,11HPROBABILITY,11,
   1AYEAR,18)
   GO TO 53
46 IF(KK.EQ.3)GO TO 47
   CALL CALCH1(N,X,Y,0,T2,T1,0.0,1.00,10.0,8.00 (SHIP TEMPERATURE M
   MODIFICATION YEAR=,37,17HTEMPERATURE DEG C,17,11HPROBABILITY,11,
   1AYEAR,18)
   GO TO 53
47 CALL CALCH1(N,X,Y,0,T2,T1,0.0,1.00,10.0,8.00,45HCONTRAST TEMPERATU
   RE 10,11,NOON,1,2,3 YEAR=,45,17HTEMPERATURE DEG C,17,11HPROBABIL
   ITY,11,AYEAR,18)
   GO TO 53
48 CALL CALCH1(N,X,Y,0,T2,T1,0.0,1.00,10.0,8.00,44HDAY NIGHT TOTAL CO
   NTRAST TEMPERATURE YEAR=,44,17HTEMPERATURE DEG C,17,11HPROBABI
   LITY,11,AYEAR,18)
53 CALL GRID(C,0.0,1.00,1.00,10,M)
   CALL SYMPL4(1.0,6.5,2.2,6HMONTH=,3.,5)
   CALL NUMR(2.2,6.5,0.2,AMON,C,,-1)
55 CONTINUE
   CO 68 K=1,LL
   NO(K)=J
60 PROB(K)=J.
   RETURN
   FNC

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